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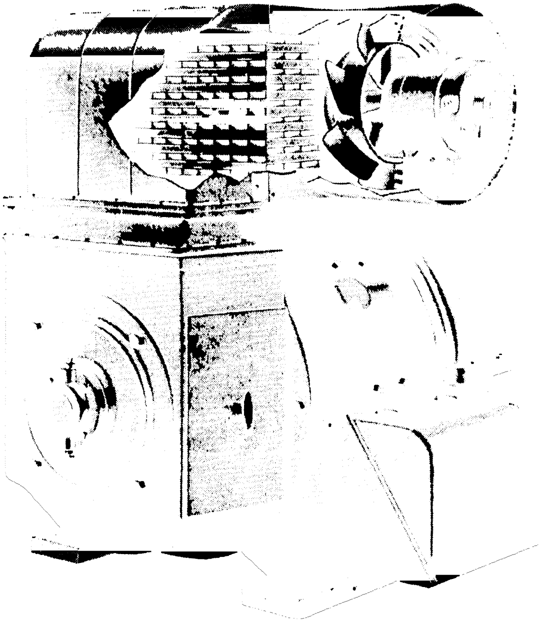

UNIT COOLED 60 HORSEPOWER DIRECT CURRENT MOTOR
GENERAL ELECTRIC COMPANY

Motor Manual

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Preface

The increasing use of electronic rectifiers together with newly developed methods of control has led to a renewed interest in the Direct Current Motor. While it is not anticipated that the direct current motor will ever completely supplant the widely-used alternating current motor, there is little doubt that the modern direct current motor is particularly suited to certain specialized applications, such as those requiring precise regulation and control.

This book has been written for those persons who are active in the selection, installation, operation, and maintenance of the modern direct current motor and its associated control equipment. Elements of design have been touched on for those who might find it necessary to make slight modifications of their equipment for some special purpose. Motor windings have been discussed, but rewinding instruction is not included as it may be found in a number of standard texts on this subject.

In order to make this volume as useful as possible, numerous published textbooks, technical papers, and trade literature were freely consulted. To the authors of these works, the writer gratefully acknowledges his indebtedness. Special acknowledgment must also be made to the American Institute of Electrical Engineers, American Leather Belting Association, National Board of Fire Underwriters, and National Electrical Manufacturers Association, for permission to use extracts from their Codes and Standards. Acknowledgment is also due to the many equipment manufacturers who furnished a large part of the illustrations. These are individually acknowledged in the text.

It is the hope of the writer that this book will prove to be a practical reference manual.

H. S. Dusenbery

San Francisco, California

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Direct Current Motor Manual

CHAPTER 1 Basic Principles

BY DEFINITION, an electric motor is a machine for converting electric energy into mechanical energy. The motors discussed here are machines which are supplied with electric energy in the form of a continuous flow of unidirectional current—that is, direct current.

The motion of a motor is the result of the reaction between two separate magnetic fields. These two fields may be either entirely independent of one another or, more often, closely related to and dependent on each other. One magnetic field is due to the flow of current in a set of conductors mounted on a rotating shaft called the *armature*. The other magnetic field is set up by the flow of current in a set of conductors wrapped around fixed pole pieces. These pole pieces are usually an integral part of the machine frame. This fixed magnetic field, in which the armature rotates, is called the *field*. To properly understand just what takes place within a direct current motor, the fact that there are two distinct magnetic fields must always be kept in mind.

To comprehend how motion is produced in an electric motor, the two magnetic fields must be examined in relation to each other.

The first magnetic field, that around a conductor which is free to move, appears as shown in Fig. 1. This is an end view of a conductor with the current flowing away from the observer. The magnetic field due to the current flow moves in a clockwise direction as indicated by the arrows. It is often called a *rotating* magnetic field. There is a simple rule for determining the direction of this rotating magnetic field when the direction of the current flow is known. With the *right hand* grasp the wire so that the thumb points in the direction of the flow of current. Then the remaining four fingers will be curled around the conductor in the direction of the magnetic field. This is shown in Fig. 2.

The second magnetic field, that set up by the fixed pole pieces, appears as in Fig. 3. Here the direction of the magnetic field is, by convention, from the north pole to the south pole. In the figure, the poles are represented as the ends of bar magnets. The lines representing magnetic force pass out of the north pole and enter into the south pole.

When these two magnetic fields are combined as shown in Fig. 4, the lines of magnetic force around the conductor free to move react with the lines of force in the fixed magnetic field and thereby compel the free conductor to move. This is because the lines of force around the free conductor cause the lines of force in the fixed field to bunch on one side of the conductor. These bunching lines of force try to straighten themselves out so that they can travel in a direct uninterrupted path, and in their effort to do so, they push the free conductor out of their way. This causes the free conductor to move at right angles to the direction of the fixed magnetic field. The rule for determining the direction in which the conductor will move is known as Fleming's *left hand* rule for motors. Using the left hand, point the forefinger in the direction of the magnetic lines of force of the fixed field, the middle finger in the direction of the current flowing in the free conductor: the thumb will point in the direction in which the conductor tends to move. All fingers are held at right angles to each other as shown in Fig. 5.

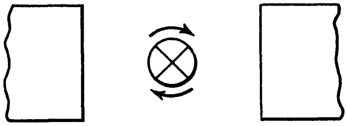


FIG. 1 Magnetic field around a conductor set up by current flowing away from observer.

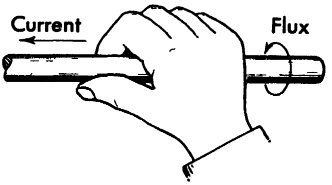


FIG. 2 The right hand rule for determining the direction of the magnetic field around a conductor.

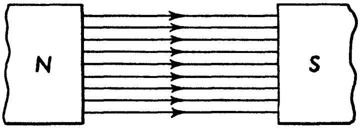


FIG. 3 The fixed magnetic field.

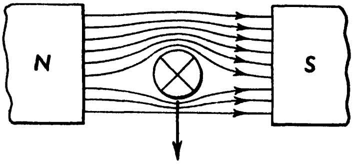


FIG. 4 Lines of force from the fixed magnetic field tend to push the conductor downward.

The *force* on a conductor carrying current in a fixed magnetic field is directly proportional to the strength of that field, the magnitude of the current in the conductor, and the effective length of the conductor. (The effective length of a conductor is the measurement of that part of the conductor which is actually in the uniform magnetic field and at right angles to that field.) The force on such a conductor can be computed numerically from

$$F_{(lb)} = \frac{8.85 \times I \times L \times B}{100{,}000{,}000} \tag{1}$$

where

F is the force expressed in pounds.
I is the current in amperes.
L is effective length of conductor in inches.
B is flux density expressed in lines of force per square inch.

This equation is little used in practice; it is given here merely to show the direct relationship between the factors involved.

The force that tends to produce and maintain rotation is called *torque*. To express torque numerically, not only must the magnitude of the force be known, but also the radius or lever arm. Reference to Fig. 6 will make this clear. At (a) a force of 3 pounds is shown acting at a radius of 1 foot. Here the torque is equal to 3 × 1 or 3 pound-feet. At (b) the same force acts at a radius of 2 feet, hence the torque here is 2 × 3 or 6 pound-feet. Torque is expressed in *pound-feet* to distinguish it from foot-pounds, the unit of work.

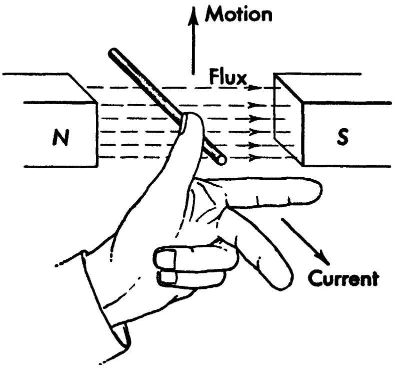


FIG. 5 Fleming's left hand rule for motors.

Up to this point, the discussion has been confined to a single conductor in a magnetic field. The next step is to place a *loop* of wire in the fixed magnetic field. Figure 7 shows the end view of a loop of wire, that is, a coil of one turn, in a magnetic field. The direction of the current flow in the loop is indicated by the dot which represents the point of an arrow coming directly toward the observer. The X represents an end view of the tail of the arrow moving into the paper and away from the observer. This is standard representation in electrical diagrams. In Fig. 7, one force acts on that part of the coil adjacent to the north pole tending to pull it downward, while the force acting on the conductor adjacent to the south pole tends to force it upward. The two forces form a couple which acts to turn the loop into the position shown in Fig. 8.

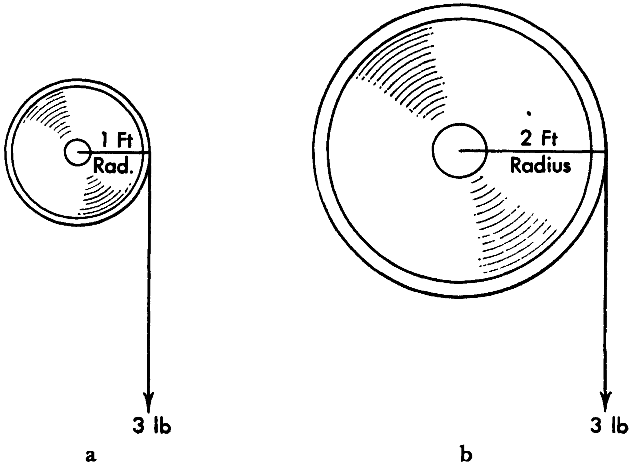


FIG. 6 Torque depends on the magnitude of the acting force and the length of the lever arm.

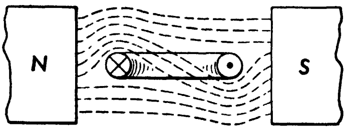


FIG. 7 End view of a loop of wire in a magnetic field. Torque is a maximum when the loop is in the position shown.

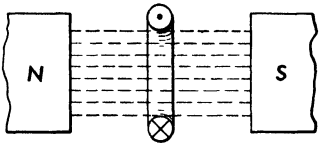


FIG. 8 End view of a loop of wire in a magnetic field. Torque is a minimum in the position shown.

When the coil reaches the position of Fig. 8, it comes to rest, as there are no longer any *turning* forces acting on it. This is the position of zero torque. Now let the loop be carried just beyond the position of zero torque and at the same time reverse the direct of the current flow in it. It is obvious that now the loop will continue to rotate another half turn.

If the current is continually reversed every half turn, the loop will keep rotating. This is an elementary electric motor.

To cause the current in the loop to reverse its direction of flow as it rotates, a *commutator* is used. Figure 9 shows a simple two-segment commutator connected to a single loop of wire. The commutator actually serves a twofold purpose. First, it is a means to supply current to a moving loop and, second, it changes the direction of the current flow in the loop as it turns.

Commercial motors are made up of a large number of rotating loops called *coils* (the armature), in order to develop a greater torque. Because there are many loops, the commercial commutator consists of a large number of separate segments.

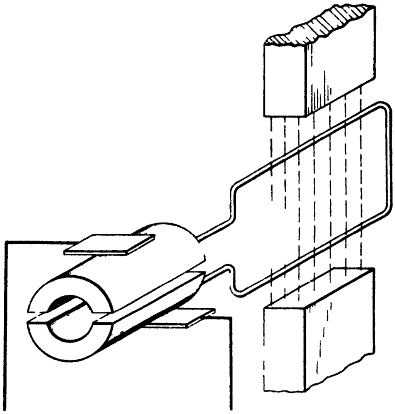


FIG. 9 An elementary two-segment commutator attached to a loop of wire in a magnetic field

In the single coil motor, the direction of the current changes when the coil rotates a half turn or through an angle of 180 degrees. In other words, when the coil has moved from the north pole of the fixed field to the south pole of the field, it has passed through 180 degrees. In motors where there are two or more *pairs* of magnetic poles, when the coil has passed from a north pole to the next adjacent south pole, it is said to have passed through 180 *electrical degrees*. For example, in a four-pole motor, a coil will move from one pole to the next in a quarter turn. Physically, the coil has moved through 90 degrees but electrically it has passed through 180 degrees.

It has already been mentioned that in order to develop a greater torque, the number of rotating coils is increased. It is obvious from the elementary diagrams (Figs. 7, 8, and 9) that more coils could easily be added. The additional coils and the methods of connecting them will be discussed in the chapter on armature windings.

There is another factor involved in producing torque. This is the strength of the fixed magnetic field. Increasing the field strength is accomplished by winding a number of turns of wire around the fixed pole pieces through which an electric current flows

Fundamentally, the torque produced by a motor is directly proportional to the armature current and the strength of the fixed magnetic field This is an important basic relationship It is expressed mathematically by the equation

$$T = KI\phi \tag{2}$$

where

K is a constant depending upon the design of the motor
I is the current in amperes flowing in the armature coils
ϕ is the magnetic flux entering the armature from one north pole of the fixed field

This indicates that to increase the torque of a motor, either the armature current or the strength of the magnetic field (or both) must be increased It should also be pointed out that when the field strength is weakened, torque is reduced This is an important consideration in motor speed control, which will be discussed later

When any conductor cuts through a magnetic flux there is an electromotive force induced in the conductor This is the basic principle of the electric generator In an electric motor, the conductors on the rotating armature cut a magnetic flux just as those on a generator armature do This causes an *induced* electromotive force to flow in the armature conductors This induced electromotive force is in a direction opposing the electromotive force impressed on the motor armature from the supply line Since this induced electromotive force opposes the impressed electromotive force and since it tends to impel a current in an opposite direction to that which causes the motor to turn, it is called the *counter* electromotive force of a motor

The induced electromotive force is never as great as the impressed electromotive force The difference between the amount of the impressed electromotive force and the amount of the counter electromotive force is termed the *effectual* electromotive force This may be only a few volts even when the impressed electromotive force from the supply line is several hundred volts

The terms impressed electromotive force, counter electromotive force, and effectual electromotive force should be clearly understood as they will be used frequently in the discussion of d-c motors. It should be noted particularly that when a motor is at rest, there is no counter electromotive force. The counter electromotive force comes into being only when the armature conductors move in the magnetic field.

Let V equal the impressed voltage and E equal the counter electromotive force (voltage), then

$$\text{Effectual Voltage} = V - E$$

Now from Ohm's law, the armature current may be found when the armature resistance and the effectual voltage is known. This is

$$I_a = \frac{V - E}{R_a}$$

where I_a is the armature current and R_a the armature resistance. This expression may also be written as

$$E = V - I_a R_a \tag{3}$$

The speed of a motor is directly proportional to the counter electromotive force and inversely proportional to the strength of the magnetic field. This may be expressed as

$$S = K\frac{E}{\phi}$$

where

S is the speed of the motor.
K is a constant depending on construction of the motor.
E is the counter electromotive force.
ϕ is the strength of the magnetic field.

Now since E is equal to $V - I_a R_a$ from equation (3), the equation for the speed of a motor may be written as

$$S = K\frac{V - I_a R_a}{\phi} \tag{4}$$

This is a fundamental motor equation for speed. It should be kept in mind when the subject of speed control is discussed.

The counter electromotive force of a motor which is running without load is almost equal to the impressed electromotive force (line voltage).

Just enough current flows through the motor to overcome friction. When a motor slows down under load, the counter electromotive force falls because the armature conductors are not cutting through the magnetic field so rapidly, and immediately more current flows through the armature. That is to say, the effectual electromotive force becomes greater. Thus the more work the motor does, the greater the current it draws.

The flow of current in a conductor causes it to heat. The more current that flows, the hotter the conductor will become. Since it has just been pointed out that the more work a motor does, the more current it draws, it can readily be seen that the amount of work a motor is able to do is limited by heat. When a motor gets too hot, it is said to be overloaded. If the overload is too great or continues for too long a time, the motor will burn out. It is well to remember that the limiting factor on practically all electrical equipment is *heat*.

CHAPTER 2 Frames and Enclosures

MECHANICALLY, a motor consists of two principal parts, the stationary member and the rotating member. The stationary member is called the *frame*. It is the supporting structure for the field pole pieces, bearings, and brush rigging. The rotating member consists of the shaft, which carries the armature winding and the commutator.

The *front* of a normal horizontal motor is the end opposite the driving pulley or coupling. The commutator is located at this end. The end which carries the pulley is called the *back*. To avoid confusion it is better practice to refer to this latter end as the commutator end.

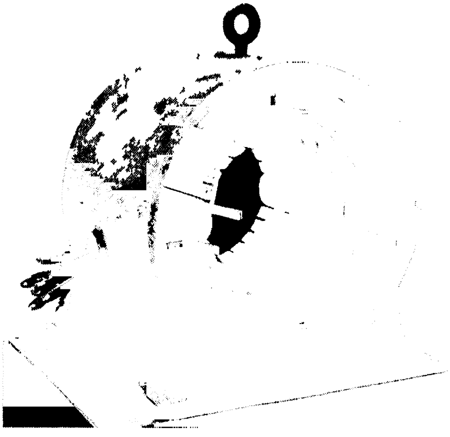


FIG. 10 Field frame of a 75 hp direct current motor The slots across the main pole pieces are for the compensating windings. (*Allis-Chalmers Mfg. Co*)

The pole pieces are usually bolted to the frame, although they may be an integral part of it. The pole pieces carry the field windings which magnetize them. The end bells, usually bolted to the main body of the frame, carrying the bearings and brush rigging. The end bells are generally considered as part of the frame. The main body of the frame without the end bells is often called the field frame. A typical field frame is shown in Fig. 10.

Frames are classified by the amount of enclosure and protection which they give the motor. The classifications and definitions given here are those of the American Standards Association.

General Purpose Enclosures

The open-type frame is usually called the *general purpose* enclosure. It is truly open and offers but little protection against falling objects and liquids. It is self-ventilating, that is, there are no restrictions to ventilation other than those necessitated by its mechanical construction. Since heat is the limiting factor of the capacity of any motor, proper ventilation is of utmost importance. Early designers felt that the more open the frame, the lower the operating temperature. The open-frame motor depends entirely on the insulating materials used in its windings for whatever degree of mechanical protection it has. Figure 11 shows an open-frame motor of the older type. Today there is a growing tendency to design general purpose motors with a more or less partially enclosed frame. This can be done because of new and improved insulating materials which operate at higher temperatures, and because of better design of the internal air circulating passages. In any event, the general purpose motor is only suited for ideal operating conditions where there is little or no danger of falling objects, liquids, dust,

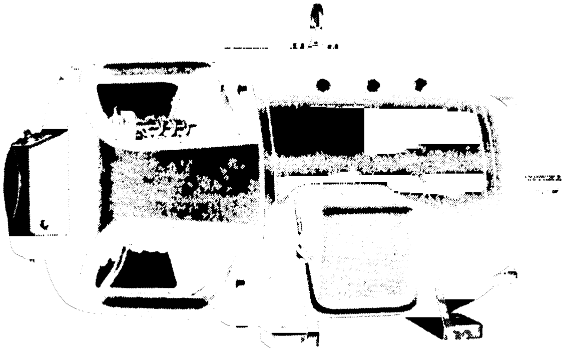


FIG. 11 Typical open style d-c motor. (*Century Electric Co.*)

fumes, etc., coming in contact with the windings. The majority of the older motors are of the open frame general purpose type. .

Protected and Semi-protected Motors

A protected machine is one in which all ventilating openings in the frame are protected with wire screen, expanded metal or perforated covers, the openings in which do not exceed ½ square inch in area and are of such a shape as not to permit the passage of a rod larger than ½ inch in diameter. Where the distance of exposed live parts from the guard is more than four inches, the openings may be ¾ inch in area and must be of such shape as not to permit passage of a rod larger than ¾ inch in diameter.

This type motor affords mechanical protection and is less hazardous for persons working in its immediate vicinity; but it offers no protection whatsoever against liquids, dust, or gas.

Where only the top half of the ventilating openings are thus protected, the machine is called *semiprotected.*

In most cases the open-type motor can be readily converted into a protected or semiprotected machine by the simple expedient of bolting screens of the proper size and type over the existing ventilating openings. The motors shown in Fig. 12 illustrate how this may be accomplished. When old open frame motors are converted into the protected type, care must be exercised that the screens or plates do not interfere with the ventilation of the machine and that they are so fastened that they can be readily removed. This is necessary for cleaning and certain maintenance operations.

Dripproof and Splashproof Motors

A dripproof machine is one in which the ventilating openings are so constructed that drops of liquid or solid particles falling on the machine from any angle not greater than 15 degrees from the vertical cannot enter the machine directly or by striking and running along a horizontal or inwardly inclined surface. A dripproof motor is included in the group shown in Fig. 12.

The splashproof machine carries the idea a step further. In such a machine the ventilating openings are so constructed that drops of liquid or solid particles falling on the machine or coming toward it in a

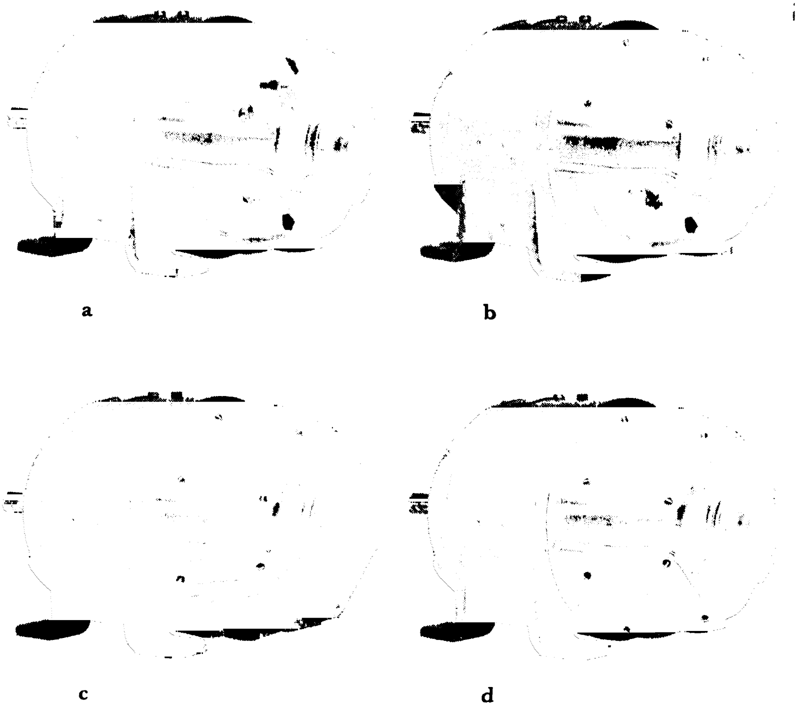


FIG. 12 Types of direct current motor enclosures.
(*a*) open type
(*b*) dripproof
(*c*) dripproof protected
(*d*) totally enclosed
(*General Electric Company*)

straight line at any angle not greater than 100 degrees from the vertical cannot enter the machine either directly or by striking and running along a surface.

In addition, the windings of the dripproof and splashproof machines are usually given special treatment to make them suitable for operation where the ventilating air is of high moisture content. Such motors are extensively used in the food industries. They are ideally suited for use in dairies, breweries, canneries, and certain marine applications. The higher initial cost of these machines is more than offset by their longer life and reduced maintenance expense.

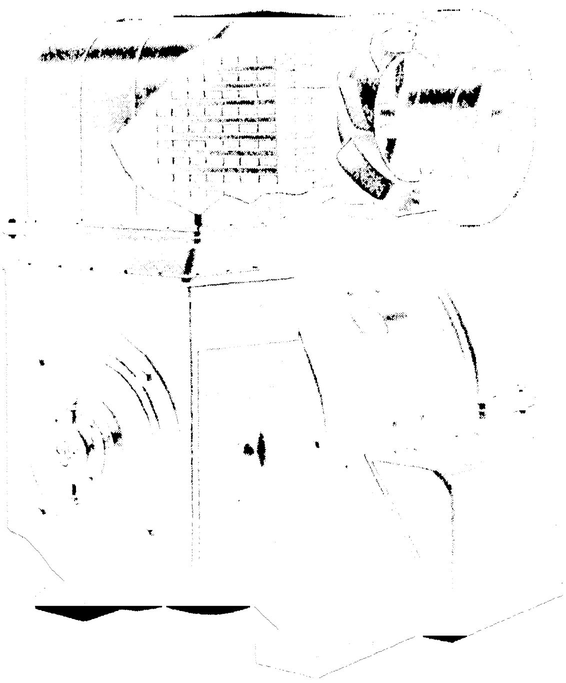


FIG. 13 Self contained unit cooled motor. (*General Electric Company*)

Totally Enclosed Motors

Totally enclosed motors are designed so that no outside ventilating air enters the motor, but they are not sufficiently enclosed to be termed airtight. The heat generated within the motor, in one type, is dissipated entirely by radiation from the enclosing frame. This frame is often provided with fins to increase the area of the radiating surface. Motors of this type are generally made with well-sealed joints and have good running seals where the shaft passes through the bearing housing. A self-contained unit-cooled motor is shown in Fig. 13. A fan circulates air through the cooler unit, down into the motor and then back through the cooler unit.

There are other types of totally enclosed machines which are ventilated by external means. These motors are provided with inlet and outlet ducts but are otherwise totally enclosed. A fan, usually located some distance from the motor, forces clean dry air through the ducts, thus preventing the motor from overheating.

In another type of totally enclosed fan-cooled motor, the motor proper is completely encased but around this inner case is an outer shell. A fan, external to the inner case and protected by the outer casing, blows air through the space between the inner and outer enclosures and thereby dissipates heat more rapidly from the inner motor case. Such totally enclosed fan cooled motors are usually less expensive than the nonventilated type, particularly in the larger sizes.

An explosion-proof machine is one in an enclosed case which is designed and constructed to withstand an explosion of a specified gas or dust which may occur within it, and to prevent the ignition of the specified gas or dust surrounding the machine by sparks, flashes, or explosions of the specified gas or dust which may occur within the machine casing.

It is customary to classify explosion-proof motors into two general types: gas explosion-proof and dust explosion-proof. The former are used in certain hazardous gas atmospheres, the latter in hazardous dust atmospheres. Both types of motors have the same general construction as standard totally enclosed and enclosed fan cooled motors but the details of construction are adapted to the specific requirements.

Gas explosion-proof motors are available that are suitable for operation in hazardous locations classified in the National Electric Code as Class I, Group D. Included in this group are atmospheres containing gasoline, petroleum, naphtha, alcohols, acetone, lacquer, solvent vapors, natural gas, and gases of similar hazard. These motors are constructed with such strength and wide metal-to-metal joints that they can withstand an internal explosion and prevent the passage of dangerous sparks or flame to the surrounding atmosphere.

Dust explosion-proof motors are available that are suited for operation in the following classified hazardous dust atmospheres:

1. Class II, Group E locations containing hazardous metal dusts such as magnesium and aluminium.
2. Class II, Group F locations containing hazardous coal, coke or carbon black dusts.
3. Class II, Group G locations containing hazardous grain dusts as found in flour mills, feed mills, grain elevators, starch, sugar or cocoa plants and locations of similiar hazard.

A waterproof machine is a totally enclosed machine so constructed that a stream of water from a hose not less than 1 inch in diameter under a head of 35 feet and from a distance of about 10 feet can be played on the machine without leakage. Leakage which may occur around the shaft may be considered permissible provided it is prevented from entering the oil reservoir and provision is made for automatically draining the machine. The machine should be provided with a check valve for drainage or with a tapped hole at the lowest part of the frame, which will serve for application of a drain pipe or drain plug.

A submersible machine is one so constructed that it will operate successfully when submerged in water under specified conditions of pressure and time. This type motor is frequently used in connection with submersible pumps.

All motor manufacturers have standardized the frame of the motors they offer and have assigned frame numbers or symbols to designate

TABLE I Principal Types of Motor Enclosures
(*General Electric Company*)

Conditions around Motor	Direct Current Type
Normal service	Open
Flying objects and dripping liquid	Open—fractional horsepower sizes Protected -integral horsepower sizes Dripproof protected—integral horsepower
Splashing, hosing	Splashproof
Extreme dust or corrosive fumes; or extreme moisture, acids, alkalis	Totally enclosed to 3 HP Totally enclosed fan-cooled to 60 HP Totally enclosed, separately ventilated
Outdoor, mild climates	Enclosed, waterproof—fractional horsepower. Splashproof— integral horsepower
Outdoor, damp and cold	Enclosed waterproof—fractional horsepower Totally enclosed, waterproof to 3 horsepower Totally enclosed, fan-cooled waterproof
Explosive gases	Explosion-proof for Class I, Group D conditions
Explosive dusts	Motors for Class II, Group G conditions
Coal dust and gas in mines	Class BM motors—inspected and tested by Bureau of Mines

each size and type. This information is usually found on the name plate of the machine. It is particularly important to mention the frame number, as well as the other information found on the name plate, when ordering spare parts or replacements for a given machine.

Table I shows the principal standard types of motors offered by the General Electric Company. Most other manufacturers offer comparable types of direct current motors, although there may be some difference in the terminology used.

CHAPTER 3 Motor Bearings

IN THE mechanical assembly of a motor, the most important units are the bearings. Rotating machinery cannot function without bearings of some type. In the direct current motor, bearing failures stand high on the list of breakdown causes. It is therefore necessary to have a good basic understanding of all types of bearings which may be encountered in motors, together with an intimate knowledge of their proper care and maintenance. In the final analysis, it is the bearings which carry the burden of the mechanical load, and unless they are correctly installed and properly cared for, the motor cannot perform efficiently. Many are the electrical failures which have their origin in faulty or neglected bearings.

Sleeve Bearings

The oldest type of bearing and one of the most common is the sleeve bearing. The essential properties of a good sleeve bearing material or alloy are specialized and exacting. There are two general types: the Babbitt metal bearing and the bronze alloy bearing.

Babbitt metal is an alloy of tin, antimony, and copper. It is strong enough to support the mechanical load of the shaft and yet soft enough to accommodate itself to the shape of the shaft. It will wipe away at any small irregular spot as the shaft rotates, so that it will clear itself before any serious damage is done.

In recent years, cast bronze has come into favor as a good bearing alloy. It is harder than Babbitt metal and does not accommodate itself as readily to the contour of the shaft. Its success is probably due to modern precision methods in its manufacture together with more accurate machining of the shaft. The standard alloy generally used in bronze sleeve bearings conforms with S.A.E. specification No. 660, which is

Copper	81 to 85%	
Tin	6½ to 7½%	
Lead	6 to 8%	
Zinc	2 to 4%	
Tensile strength, pounds per square inch		30,000
Yield point, pounds per square inch		15,000
Elongation, per cent in two inches		20
Brinnell hardness		50-60

In the properly designed and fitted sleeve bearing, the shaft actually floats on a thin wedge-shaped film of oil. There is actually no metal-to-metal rubbing, save perhaps at the instant of starting. When the shaft starts to turn, it drags with it a film of oil, and as the shaft continues to rotate, a pressure is built up which keeps a constant film of oil between it and the bearing surfaces. It is this film of oil which actually supports the load so that under normal operating conditions there is no wear on the bearing. In a finely bored small bronze bushing a film of oil of about 0.001 inch is sufficient. For ordinary bearings with steel shaft and babbitted shell bearings a thickness of oil film above 0.00075 inch should be maintained. Allowance for this oil film is made by motor designers and it is important that their recommendations should be followed when bearings are replaced. It is also important that the proper type and grade of oil be used in order to maintain this film. When the oil film fails, the bearing fails. Because of the extreme thinness of the oil film, a low-viscosity, freely flowing oil is generally used. A good grade of mineral oil having a viscosity of about 200 seconds Saybolt at 100 F is recommended.

In addition to providing a film for the shaft to float on, the oil must keep the bearing cool by dissipating the heat generated by friction of the rotating shaft. There is, of course, friction even though the shaft floats on oil. There is some controversy as to just what this friction is, but it will suffice to say that this friction does exist and must be taken into consideration. When the bearing is operating properly it becomes quite warm. However it should never get too hot to touch.

Oil is usually supplied to the standard sleeve bearing by means of a ring which rides on the shaft. As the shaft turns, the ring drags the oil out of the reservoir at the bottom of the bearing housing and carries it over the top. Grooves are usually cut in the upper half of the bearing for the sole purpose of properly distributing the oil as it flows downward. Since the turning ring causes a certain amount of the oil to splash about in the bearing housing, modern motors have sleeve bearings provided with a seal to prevent oil leakage. This is usually in the form of a felt washer that prevents air currents which in turn carry the oil on the wet surfaces out of the housing, rather than prevent the leakage of the oil itself. The felt washer should be of the best grade of felt obtainable and not less than ¼-inch thick before compression. The inside diameter of the felt washer should fit the shaft snugly. Oil leaks may be due to a poorly fitted bearing or an oil-soaked felt seal. Should a motor leak oil excessively, both the bearing fit and the felt seal should be checked. Figure 14 shows a typical sleeve bearing assembly in cross section.

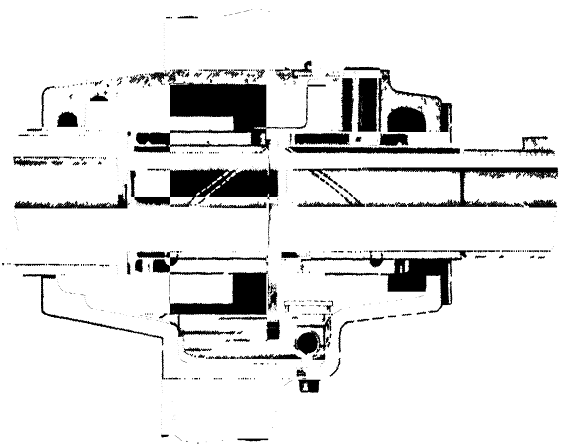


FIG. 14 Cross section of a motor sleeve bearing showing oil ring. (*Allis-Chalmers Mfg. Co.*)

The oil level in sleeve bearing housings should be checked regularly with the motor stopped. Figure 15 shows several common types of oil gauges used on motors and the proper oil level which should be maintained.

Old oil should be drained from the bearing housing at least every year. The drain plug in the bottom of the frame should be removed and any foreign matter which may have accumulated flushed out. On motors not provided with a drain plug, the end bells should be removed, the end shield rotated, and the bearing thoroughly cleaned. The end shield should then be reassembled and fresh oil added. Motors should never be oiled while running, as this may cause the oil to get into the windings or splash out on the floor.

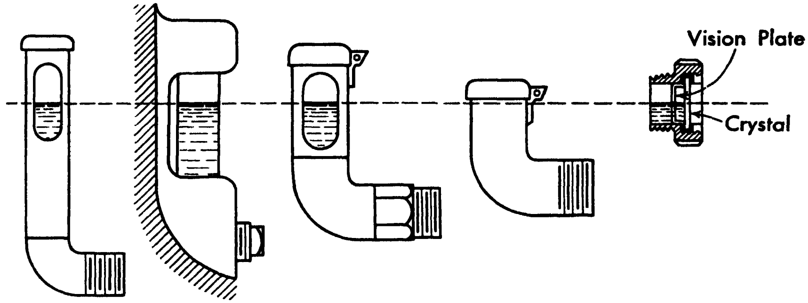


FIG. 15 Common types of oil level indicators for sleeve bearing motors. (*General Electric Company*)

Small sleeve bearing motors are sometimes lubricated by wool waste packing. The wool waste is saturated with lubricating oil. High-grade wool in the form of skeins is recommended for this purpose. Once properly packed, such a bearing requires little maintenance in normal service except for adding a few drops of oil after a thousand hours or so of operation.

Graphited sleeve bearings are used to a limited extent in certain motor applications. A graphited sleeve bearing is one in which grooves have been cut and graphite inserted under heavy pressure. Bearings of this type are used in out-of-the-way places where proper lubrication is apt to be neglected and where contact with oil or grease would be harmful to the material being handled. Approximately 40 per cent of the inside surface of the bearing is graphited. The lubricant is forced against the shaft when the bearing is warmed by the rotation of the shaft and is reabsorbed into the bearing when rotation ceases.

There is another type of self-lubricated or oil-retaining sleeve bearing known by such trade names as "Oilite" and "Compo." These bearings are made of pure metal powders die-pressed into shape and then alloyed at high temperatures. This forms a dense homogeneous metal, which is yet porous enough to contain up to 35 per cent oil by volume. Through capillary action, the oil is conveyed directly through the bearing wall to the surface of the shaft. When the shaft starts to turn, a film of oil is quickly built up. As the temperature of the bearing increases, more oil is drawn to the shaft from the pores of the bearing. When the shaft stops, the oil is reabsorbed into the bearing pores. These bearings, like the graphited type, are used mostly where regular lubrication may be overlooked.

Sleeve bearing wear is determined by measurement of the air gap between the armature and the field within the motor. Measurements made at the lowest part and on the sides will usually indicate any irregularities. A special tapered feeler air gap gauge is available for this purpose. Air gaps should be within 10 per cent as measured under like field poles around the motor. Irregular air gaps are the first sign of a worn bearing. When necessary to replace a worn bearing, the recommendations of the motor manufacturer should always be followed. It is strongly recommended that an extra set of bearings for each type of motor be kept on hand. This is necessary even when the motor is sent to an outside shop for repair, for the correct bearing may not be in stock nor obtainable on short notice. For this reason, an extra set of bearings is good insurance.

Ball Bearings

Although the sleeve-type bearing is the oldest and perhaps the most widely used type of bearing, it has several disadvantages. One of these concerns the oil film which separates the shaft from the housing. As has already been mentioned, at the instant of starting there is no oil film. This tends to cause excessive wear on high-speed motors which are started and stopped frequently. Another disadvantage concerns oil leakage and the binding of the oil ring if the motor is not horizontal at all times. The matter of oil seals, together with cumbersome bearing housings, has been a source of trouble both in the design and maintenance of motors. This has led designers to develop a rolling contact as a substitute for the sliding contact of the sleeve bearing.

This development has resulted in the ball bearing and roller bearing which are popularly called *antifriction* bearings. Actually, there is of course no such thing as a truly antifriction bearing.

In the ball bearing, a ring of polished balls is intended to replace the oil film of the sleeve bearing. The balls separate a rotating inner ring, known as the *inner race*, from the stationary outer ring, or *outer race*. In order to keep the balls properly spaced around the bearing, some form of cage or retainer is necessary. Only two or three of the balls are under load at any given instant; the remainder are carried around the shaft in the retaining ring. Without such a retaining ring, the balls would bunch and bind. There is a certain amount of slippage and sliding between the retainer and the unloaded balls. For this reason lubrication is necessary. Thus a ball bearing is composed of four parts: the outer ring, the inner ring, the balls, and the retainer. There is a wide variety of designs for each part, especially of the outer ring and retainer cage.

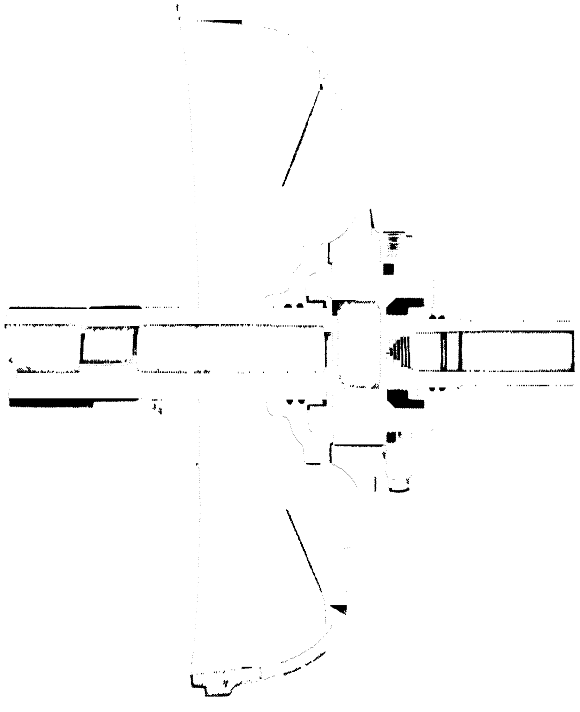


FIG. **16** Cross section of end-bell of a ball bearing motor (*Century Electric Co.*)

The ball bearing operates with less friction and the least wear of any type of bearing. It will therefore maintain its accuracy longer than any other type. Ball bearings are especially advantageous when the motor frame does not remain in a stationary position, such as on a moving vehicle. They are also used extensively when the motor is located in an inaccessible place or where the motor is totally enclosed. Ball-bearing motors usually cost slightly more than sleeve-bearing motors, but this is generally more than offset by reduced maintenance costs.

Ball bearings are manufactured to internationally standardized dimensions and any one make is exactly interchangeable with any other. This facilitates replacements. The numbers and symbols stamped on the inner and outer ring of the bearing by the manufacturer designate the size and type of the bearing. The numbering system of one manufacturer, however, is not necessarily the same as that of another. At the present time, efforts are being made to set up a standard numbering system to be adopted by all American manufacturers. Samples of these numbers will be found following the brief table listing common types of ball bearings.

More than 90 per cent of all ball-bearing failures are due to dirt which has found its way into the bearing either due to carelessness before or during assembly, or by the user after the motor has been placed into operation. Balls rolling in their groves are in actual metal-to-metal contact under great pressure. Hard particles of dirt when mixed with the lubricant in the bearing make a grinding compound which will gradually destroy the close fit and accuracy of the bearing. For this reason, great care should be used in handling ball bearings. They should never be removed from their factory wrapper in advance of actual installation.

The lubrication of ball bearings is very important. Lubrication not only must reduce the sliding friction within the bearing but also must protect the highly polished parts from corrosion. The original factory-supplied lubricant in a new ball bearing should never be washed out. Should it be necessary to add additional lubricant, care should be taken that it is absolutely clean.

A high-quality grease made especially for ball bearings should always be used. Any grease will not do. The grease should not melt at the highest operating temperature of the bearing. The oil should never separate from the base used. It should contain no material which will corrode the bearing surfaces. These are but a few of the many reasons for using a high-grade grease. Here again it is important to follow the recommendations of the motor manufacturer or the bearing manufacturer. Ball-bearing grease is usually sold in tubes so that it will not become contaminated before use. Even the best grease will become worthless if allowed to stand in open containers in a dirty or dusty atmosphere.

The General Electric Company offers the following grease specifications for use in motors of their make.

Worked consistency	300 to 320 mm/10
Flow point	280 F
Mineral oil	79 per cent minimum 220 240 viscosity at 100 F
Soap base	Sodium calcium, separately or in combination
Free alkali	0.30 per cent max. (as NaOH)
Free acid	Nil
Water	0.20 per cent max.
Ash	5.0 per cent (as sulfates)
Color	Amber

Ball bearings are first classified as single row or double row. This refers to the number of rows of balls in the bearing. They are further classified into types named after the load they are designed to carry. These are radial load, thrust load, and combined radial and thrust load.

Bearings are also available with grease retaining shields either on one side or on both sides of the bearing. The selection of the proper ball bearing is a matter for the motor designer. We are concerned only with replacements here. When a bearing becomes worn or troublesome, it should be replaced with a like bearing. The replacement does not have to necessarily be of the same manufacture, but it should be the same size and type. Specific instructions as to the removal of the old bearing and the installation of the new one may be obtained from the bearing manufacturer.

A worn ball bearing will make itself known by excessive noise and vibration. Should there be any doubt as to which is the defective bearing on a noisy motor, each bearing in turn should be checked by holding the end of a long screwdriver firmly against the bearing housing and pressing the ear to the handle of the screwdriver. This will transmit the noise of the bearing directly to the ear. The rough sounding bearing should be replaced promptly. Once a ball bearing becomes rough, it gets progressively worse very rapidly.

Table II is given here to serve as an indication of how various bearing makers designate their bearings. Only a few of the popular makes are given. Complete interchangeability tables are available from any ball bearing manufacturer without charge.

TABLE **II** Common Types of Ball Bearings

Type	Fafnir	S.K.F.	New Departure	M-R-C
Single Row	200K	6200	3200	200S
Open style	300K	6300	3300	300S
	400K	6400	—	400S
Single Row	200KD	6200Z	7500	200SF
one side	300KD	6300Z	7600	300SF
shielded	400KD	—	—	400SF
Single Row	200DD	6200ZZ	77200	200FF
double shield	300DD	6300ZZ	77300	300FF
Extended	WIR200W	6200X	4200	—
inner race	WIR300W	6300X	4300	300WI

New Recommended Bearing Notation

Sample number 20BCO2PG

First two figures (20) indicate bore in millimeters
Second two letters (BC) indicate type of bearing
Third two figures (02) indicate width and outside diameter.
Last two figures (PG) indicate closure or plate shield.

Sample Conversions

New Notation	Fafnir	S.K.F.
10BCO2	200K	6200
10BCO2P	200KD	6200Z
10BCO2PP	200KDD	6200ZZ
12BCO2	201K	6201
17BCO2	203K	6203
12BCO3	301K	6301
12BCO3P	301KD	6301Z
12BCO3PP	301KDD	6301ZZ

Lubrication of ball bearings, other than those grease packed and sealed at the factory, is generally accomplished while the motor is running. Ball bearing motors requiring lubrication are usually provided with pressure grease fittings and a relief plug at the bottom of the housing. The relief plug is first removed and grease is applied with a pressure gun. With the motor running, grease is applied until it begins to flow from the relief hole. The relief hole should be left open until all excess grease is expelled.

When it becomes necessary to lubricate a factory-sealed ball bearing, it is necessary to disassemble the bearing housing and clean both the inside of the housing and the bearing with carbon tetrachloride. When thoroughly cleansed of old grease, reassemble all parts except the outer caps or plates. Apply new grease over and between the balls, either by hand or directly from a tube. The grease should fill approximately one-half of the free space in the housing. Care should be taken throughout the entire greasing operation to prevent the entrance of dirt or foreign particles.

CHAPTER 4 The Motor Field

THE fixed magnetic field in which the armature rotates is called simply the *field.* It is produced by passing an electric current through insulated windings, called *field coils,* on iron pole pieces. This current sets up a magnetomotive force which sends a magnetic flux through a magnetic circuit. The magnetic circuit should not be confused with the electric circuit.

Figure 17 shows the path of the magnetic circuit in a four-pole motor. The lines in this figure represent the path of the magnetic flux as it passes through the frame, the pole pieces, the air gap, and the armature core. The pole coils are connected so as to form alternate north and south magnetic poles around the frame. The flux leaving a north pole divides, each half going to an adjacent south pole. This means that there is about twice as much magnetic flux in each pole piece as in any section of the armature. Actually, because of magnetic losses, less than half the magnetic flux from each pole piece is available to the armature.

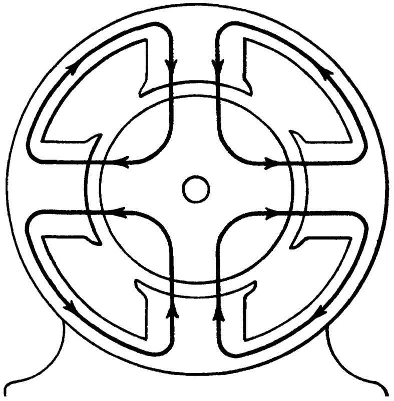


FIG. 17 Magnetic circuit in a four-pole motor. This shows the field circuit only.

The magnetic flux does not pass through all parts of the circuit with equal ease. It has more difficulty in passing across the air gap than through the iron frame. Thus the air gap is said to have a greater magnetic *reluctance* than does the iron frame. Therefore, in order to have as much magnetic flux as possible available to the armature, the air gap must be kept to a minimum. For efficient motor operation, the magnetic losses should be kept as low as possible in all parts of the magnetic circuit.

The relationship of magnetomotive force, magnetic flux, and magnetic reluctance is

$$\text{Flux} = \frac{\text{Magnetomotive force}}{\text{Magnetic reluctance}}$$

This relationship is similar to Ohm's law in an electric circuit. This indicates that for a particular value of magnetomotive force, the reluctance must be low to produce maximum flux. Various kinds of iron and steel exhibit a different magnetic reluctance. Motor designers endeavor to select the material which best satisfies the mechanical as well as the magnetic requirements. It is well to understand this when motors are dismantled for repair. Should new iron or steel be substituted for any of the original material, a marked change in motor efficiency may result if the magnetic reluctance of the magnetic circuit is changed.

In addition to selecting the proper magnetic materials, the size of the pole pieces, their shape, and the design of the armature itself, all must be considered to keep magnetic losses at a minimum.

The pole pieces are usually made up of laminated soft steel bolted to the frame of the motor. Laminated steel is used to keep eddy currents which may be set up within the pole pieces to a minimum. The energy of eddy currents is dissipated in heat, which, of course, is detrimental because it lowers the operating efficiency of the motor.

In order to keep the air gap between the tips of the pole pieces and the armature uniform, thin shims are usually placed between the base of the pole pieces and the frame. The addition or removal of even one shim will make a noticeable difference in the operation of the motor. When it is necessary to remove a pole piece, the shims (if any) should be properly tagged so that they may be correctly replaced.

The shape of the pole pieces is a matter to which motor designers have given much thought. In general, pole pieces are so shaped as to make the maximum amount of flux available to the armature conductors. To accomplish this, the ends of the pole pieces nearest the armature are usually broadened to form pole shoes. The shoes may be separate pieces of metal or merely enlarged end sections of the pole piece itself. A typical pole piece may be seen in Fig. 18. It is made up from thin sheets of steel bolted together. The individual sheets which make up the laminations are so stamped that the pole piece will have the proper shape on assembly. The finished pole piece is bolted to the frame.

There must, of course, be an even number of poles to properly complete the magnetic circuit. Small motors having but two poles are sometimes called *bipolar* motors. The majority of the modern motors have more than two poles and are known as *multipolar* machines. The multipolar machine is usually more efficient than the bipolar except in the case of very small motors.

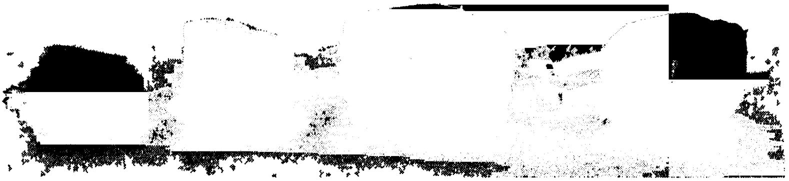


FIG. **18** (*left to right*) Commutating pole, main pole piece, shunt field coil, and compound field coil (*Allis-Chalmers Mfg Co.*)

In addition to the main pole pieces, modern d-c motors are provided with small auxiliary poles called commutating poles or interpoles. Their purpose and arrangement will be fully discussed in the chapter on commutation. In Fig. 18, a commutating pole is shown at the extreme left.

The field winding of a d-c motor determines its general type and operating characteristics. Coils made of a large number of turns of comparatively small wire are called shunt coils; those of a few turns of larger wire are the series coils. The names *shunt* and *series* are derived from the way in which the coils are connected with the armature circuit.

Field coils are usually wound on forms, and after they are properly insulated and finished, they are slipped in place on the pole piece. A typical form wound field coil appears in Fig. 18. Each field coil has its leads brought out and the final connections are made after assembly in the motor.

In maintaining field windings, cleanliness is of particular importance. Heat can not be properly dissipated from the surface of the coils if they are coated with grime and dirt. Clogging of the ventilating spaces often causes the insulation of the field coils to break down, resulting in the ultimate failure of the coil. Again, it must be repeated that excessive heat is the enemy of all motors and nothing is worse for field coils than to allow them to overheat.

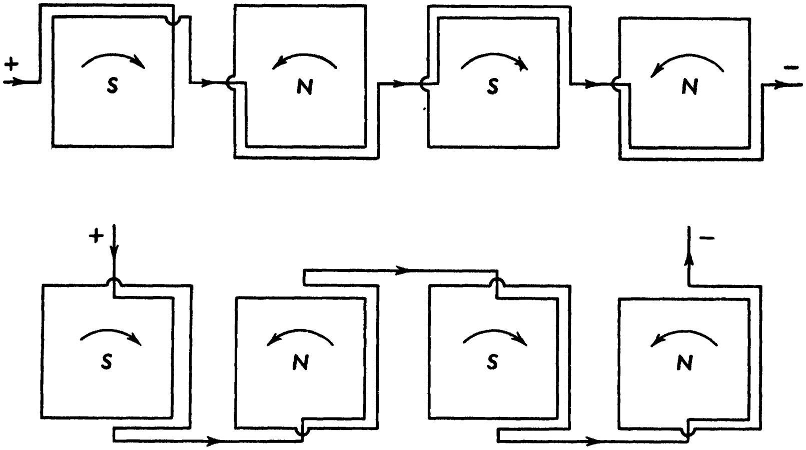


FIG. 19 Arrangement of field coil connections to insure alternate north and south poles.

One of the commonest troubles in d-c motors is caused by incorrectly connecting the field coils. Since the field coils are connected after assembly on the pole pieces, improper connections can be easily made. Each coil has its lead wires brought out separately and it is often difficult to determine which end is which. Sometimes both of the leads are brought out on the same side of the coil and sometimes they are brought out on opposite sides. In order to have alternate north and south poles around the frame, the current must flow in opposite directions in each adjacent coil. Figure 19 shows two ways in which this may be accomplished. It is often necessary to give the coils a half turn before assembling them on the pole pieces in order to correctly connect them.

The simplest way to determine the polarity of a field coil is by use of a pocket compass. This can be done by connecting the coils in series and applying the current before the coils are assembled on their pole pieces.

The coils should be kept well spread apart and the compass should be slowly brought to each coil in turn from a distance of several feet. The compass needle is observed as the compass is brought near the coil. Every other coil in the series should attract the same end of the compass needle. The connections are marked during this test to facilitate the final connecting after the coils have been mounted in place. After the final connections have been made, the polarity of each field coil should again be checked with a compass before the motor is placed in service.

When testing for polarity with the ordinary pocket compass, care should be taken to always hold it in such a position that the needle is free to move. The polarity of the compass itself may become reversed during the testing because of the enormous magnetic strength of the field coils as compared with that of the compass needle. The compass should be checked both before and after testing each individual coil to see that the proper end of its needle points north. It is customary to repeat the entire test two or three times to avoid any possibility of error.

This arrangement of the field coils applies to either the shunt-connected field coils or the series-connected field coils. In the compound wound motor, both series and shunt coils are present. The shunt winding is often placed over the field pole first and then the series winding placed on top of it. In some compound motors, the series coil is wound with rectangular wire or copper ribbon and is mounted around the outside of the shunt coil in an edgewise position. In any case, these two windings are separate, independent coils, and each is carefully insulated from the other. Each coil has its own set of terminals brought out and is usually individually connected to its counterpart on the next pole.

Unit construction of the coils in the field winding is customary so that should a defect develop in any one coil, that coil may be easily replaced without disturbing any of the others. It can not be emphasized too strongly that when such a replacement is made, the polarity must be checked and double-checked before the motor is returned to service.

Normally, the series and shunt field coils of a compound motor are so connected that they have the same polarity. Thus one coil may be thought of as aiding the other. This is called a *cumulative* compound motor. In certain applications, the series and shunt windings are so connected that they are of the opposite polarity. Such a motor is called a *differential* compound motor. Some motors have a very light series field used merely for stabilizing purposes. This type of motor is known as a *stabilized shunt* motor. The operating characteristics of these various motors will be discussed later.

The amount of magnetic flux produced by a motor field coil depends on the character of the iron or steel used in the pole itself, the amount of that material, the number of turns of wire in the field winding, and the current (amperes) flowing through the winding. Each of these factors has very definite limitations. The particular kind of material used in the pole construction has an ultimate magnetic saturation point. The space available within the motor limits the pole size as well as the number of turns of wire which may be placed around the pole. Finally, the number of amperes the coil can safely carry is limited by heat. All of these factors must be considered and balanced, one against the other, in the design of a field winding.

If the resistance of a field winding is reduced either by using a lesser number of turns of wire or a large size wire, more current will flow and there is danger that the coil will overheat. On the other hand, if the bulk of the coil is increased by using more turns of wire, the ventilation spaces may be blocked This again may cause the coil to overheat. Magnetic flux is the product of the current in amperes times the number of turns (ampere-turns). Any change in either factor changes the magnetic flux of the motor field, assuming that there is no change in the material content of the pole piece. It is therefore recommended that when a field coil is repaired or replaced, the new winding should be an exact duplicate of the original winding.

The field coils of a motor require the minimum of maintenance. If they are kept clean and the ventilating spaces kept open, the field coils will seldom overheat. The connections should be checked from time to time to see that they have not worked loose. Field coils that are cool and clean rarely give trouble.

CHAPTER 5 The Armature

THE rotating part of the direct current motor is called the *armature.* It is an assembly consisting of the armature core, the armature windings, and the commutator.

The material used in the armature core must have high permeability, low hysteresis loss, high electric resistance, and good mechanical strength. Certain silicon steels fulfill most of these requirements and are the materials generally used.

High permeability refers to the ease with which the magnetic flux passes through the core. The magnetic circuit shown in Fig. 17 passes from the field poles across the air gap and through the armature core. It must pass through the armature core easily so that the maximum flux can be utilized by the armature windings. The more flux available to these windings, the greater the electrical efficiency of the motor. These are a few of the reasons for stating that the armature core material should have high permeability.

Since the armature core passes alternately under the north and south field poles as it rotates, there is a continual reversal of magnetism within the steel core. Material which has the ability to reverse its magnetic polarity easily and with the expenditure of a minimum amount of energy is said to have a low hysteresis loss. The value of the hysteresis loss depends upon the amount of the flux passing through the core, the speed of the motor (number of magnetic reversals), and the character of the material used. For high efficiency the core must be of a material with a low hysteresis loss.

Since the core is revolving in a magnetic field and since its material is an electric conductor, generator action exists; that is, voltages are induced which cause currents to flow in the core material. These currents are called *eddy currents.* It is important that the armature core offer a high resistance to these eddy currents, otherwise they will waste energy by heating the core. Therefore in addition to selecting a steel with a high electric resistance, the core is made up of thin laminations (about $\frac{1}{64}$-inch thick) arranged at right angles to the path of the eddy currents. These thin layers of metal are steel stampings usually coated with varnish to insulate them from each other. The varnished coating has the effect of breaking up the path of the eddy currents and thus holding them to a very low value.

Finally, the material must have good mechanical strength to withstand the centrifugal force due to the speed of rotation.

The core is provided with slots in which the armature coils are placed. The size and shape of these slots depend to a certain extent on the type of armature winding used. They are generally designed so that the armature windings will be firmly held in their proper position and will not work loose even when the assembly rotates at high speed.

Ventilating ducts are usually provided in the core to reduce the possibility of the armature assembly overheating. These ducts are of two general types. One type of duct passes through the core in the same direction as the shaft, that is, from end to end. These ducts appear as holes in the individual core stampings. As the stampings are assembled to build up the core, the holes are aligned to form a continuous opening through which the air flows. These ducts are known as axial ducts. The second type of duct passes from the outer surface of the core to the inside. Such ducts are formed by placing spacers between the steel stampings as they are assembled. They are known as radial ducts. Both types are usually present, particularly in the larger motors.

In addition to the ventilating ducts, some motors are provided with fan blades mounted directly on the shaft for the purpose of circulating air through the entire motor.

Figure 20(a) illustrates an armature core with the commutator assembled on the shaft. There are no windings on this assembly but the slots in which the windings are placed can be clearly seen.

When the laminations are assembled, they are usually clamped over a cast iron spider which in turn is keyed to the shaft. Mechanical details of this arrangement differ with the various makes and sizes of motors. In general, the entire armature assembly is so arranged that the shaft may be removed if necessary without destroying the balance of the assembly.

As the armature coils rotate, it is necessary to supply them with current flowing in the proper direction. This current must reverse its direction of flow in each coil as that coil passes from under one magnetic pole to the next. To accomplish this, a *commutator* is used. The commutator is made of wedge-shaped segments of copper insulated from one another by thin layers of mica. The segments are held together by a circular-clamp fitting into a V-shaped ring designed to pull the segments inward to form a rigid assembly. The clamp is prevented from short circuiting the copper segments by rings of built up mica sheets. Figure 21 shows a typical commutator assembly. The V-shape construction of the modern commutator is the result of years of operating experience, during which time innumerable designs were tried and discarded. No other insulating material has been found equal to mica

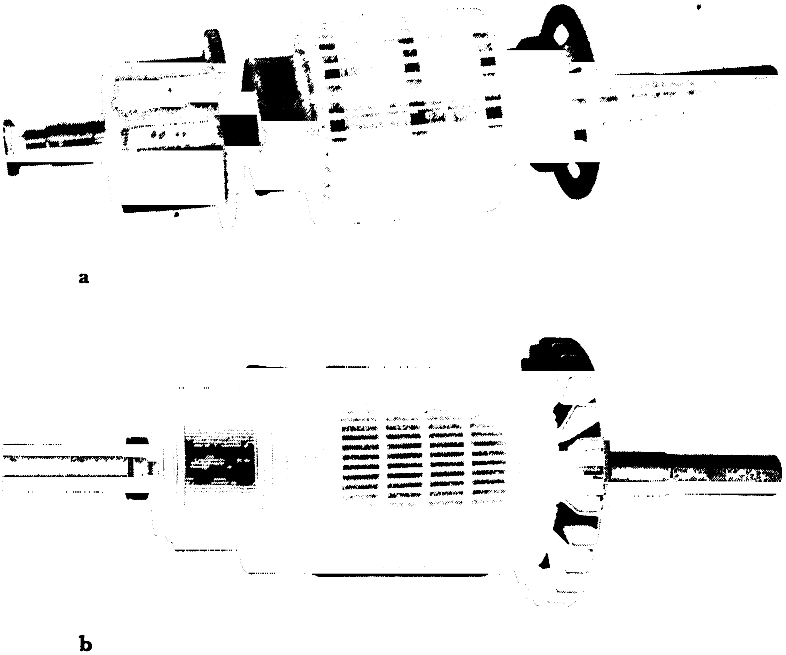


FIG. 20 Typical d-c motor armature.
(*a*) Armature core and assembled commutator without winding. (*Allis-Chalmers Mfg. Co.*)
(*b*) Finished armature. (*Century Electric Co.*)

in commutator construction for this material does not absorb oil or moisture.

The individual copper bars are usually higher at one end. This is called the riser. Small slits are usually provided in the riser into which the leads from armature coils are soldered. These can be seen in Fig. 20.

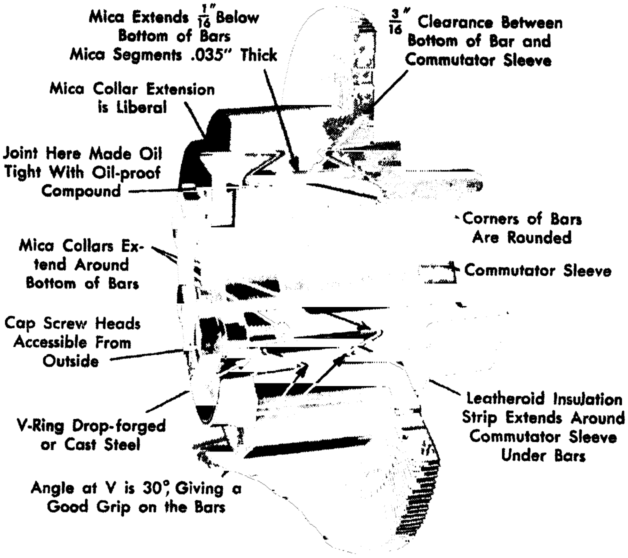

Mica Extends 1/16" Below Bottom of Bars
Mica Segments .035" Thick
3/16" Clearance Between Bottom of Bar and Commutator Sleeve
Mica Collar Extension is Liberal
Joint Here Made Oil Tight With Oil-proof Compound
Corners of Bars Are Rounded
Mica Collars Extend Around Bottom of Bars
Commutator Sleeve
Cap Screw Heads Accessible From Outside
Leatheroid Insulation Strip Extends Around Commutator Sleeve Under Bars
V-Ring Drop-forged or Cast Steel
Angle at V is 30°, Giving a Good Grip on the Bars

FIG. 21 Cutaway view of a typical commutator. (*Reliance Electric & Engineering Co.*)

Since the mica strips between the copper segments do not wear away as quickly as does the copper, it is customary to cut away the mica so that it is slightly lower than the copper surface of the commutator. This is known as *undercutting* and is a common maintenance operation. When the mica protrudes above the copper surface of the commutator, the condition is popularly referred to as *high mica.*

The number of bars and their size in a given commutator is a matter of motor design. It is very unfortunate that little or no effort has been made by motor designers to develop standardized commutator designs. As a result, it is almost impossible for even the largest supply houses to maintain an adequate stock of replacement commutators. Motor users will do well to have a spare commutator on hand at all times, regardless as to whether they operate their own repair shops or depend upon outside shops.

The number of bars in a commutator depends upon the type of the armature winding and the number of sections the winding contains. In general, increasing the number of bars diminishes the tendency of sparking. For efficient motor operation without the risk of flashovers on the commutator, the voltage between adjacent commutator bars is held to a low value. In a well-designed motor, the voltage between bars is generally less than 15 volts.

CHAPTER 6 Armature Windings

THE armature winding of the modern d-c motor is generally a form of *drum winding*. An older form known as the Gramme ring winding is obsolete and is seldom encountered in existing motors. In the drum winding, all the conductors are in slots close to the outer surface of the armature core. They are appropriately connected to the commutator to form one or more electrical paths.

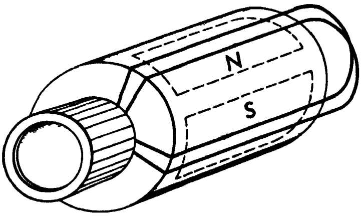


FIG. 22 Elementary lap type armature winding.

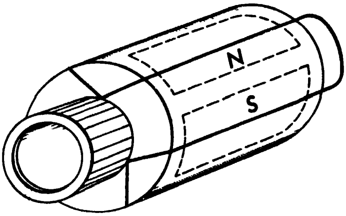


FIG. 23 Elementary wave type armature winding.

There are two basic types of drum windings; the lap winding and the wave winding. The difference in the two types is in the manner of connecting the armature coils to the commutator. In the lap type of winding, the two ends of the individual armature coils are connected to adjacent commutator segments. This is shown in Fig. 22, where two coils of a lap winding are indicated. In the wave type, the coil ends are connected to commutator segments which are approximately 360 electrical degrees apart. The wave winding is shown in Fig. 23. The dotted areas in both sketches indicate the position of the north and south field poles so that the relation between the sides of the coils with respect to the field poles can be seen.

The straight portion of the armature coil, that part which is in the slot and cuts through the magnetic field, is called the *inductor*. The remaining portion of the coil is known as the end connection.

The individual coils are usually wound, shaped, and insulated before they are installed in the slots on the armature core. Figure 24 shows the shape of one coil with leads arranged for the lap winding, whereas Fig. 25 shows a coil arranged for a wave winding. The spacing of the coil terminals which connect with the commutator being the distinguishing feature. *A* and *B* designate the coil sides or inductors. The dotted portion represents that part of the coil in the bottom of the armature slot while the solid lines represent the coil side uppermost in the slot.

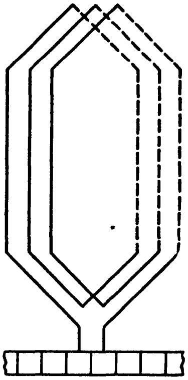


FIG. 24 Lap wound armature coil. Note that the coil terminals are connected to adjacent commutator bars.

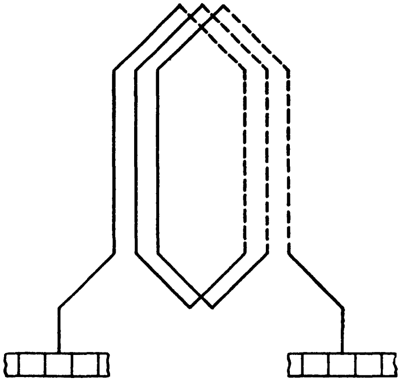


FIG. 25 Wave wound armature coil. Note the position of the coil terminals.

The peculiar twist in the end of the coil is necessary so that the coil will lay smoothly in its proper position in the armature slot. In the general arrangement of the coils in a lap winding, one side of the coil is the uppermost inductor in the slot while the other side of the same coil is in the bottom position. Figure 26, showing a typical lap winding, will make this arrangement clear. In the winding shown in this figure, there are two coil sides (or inductors) in each slot. Such a winding is called a *simplex* winding to distinguish it from the *multiplex* winding where there are more than two coil sides in the slot.

The span of the coil, called the *coil pitch*, is usually approximately equal to the pole spacing (pole pitch) so that when one side of the coil is under the center of a north pole, the other coil side is under a south pole. This, however, is subject to a certain amount of variation in motors of different design.

In the simple two-layer lap winding of Fig. 26, it is standard practice to number the coil sides starting with a side in the top of the slot as *1* and the side directly below as *2*. Moving to the right, the adjacent top coil is *3*, that below it *4*, and so on around the armature. The number of elements that a coil connection spans on the commutator side of the armature is called the *front pitch;* the number spanned at the opposite end of the armature is known as the *back pitch.* In Fig. 26, coil side *3* connects with coil side *10* at the front of the armature through a commutator segment, hence the front pitch is 10 — 3 or 7. At the rear of the armature, coil side *1* connects directly to coil side *10*, hence the back pitch of this winding is 10 — 1 or 9. In numbering the coil sides, those at the top of the slot are all odd numbers (1, 3, 5, 7, etc.), while those at the bottom are even numbers (2, 4, 6, 8, etc.). Since all connections are made from inductors (coil sides) at the top of the slot to

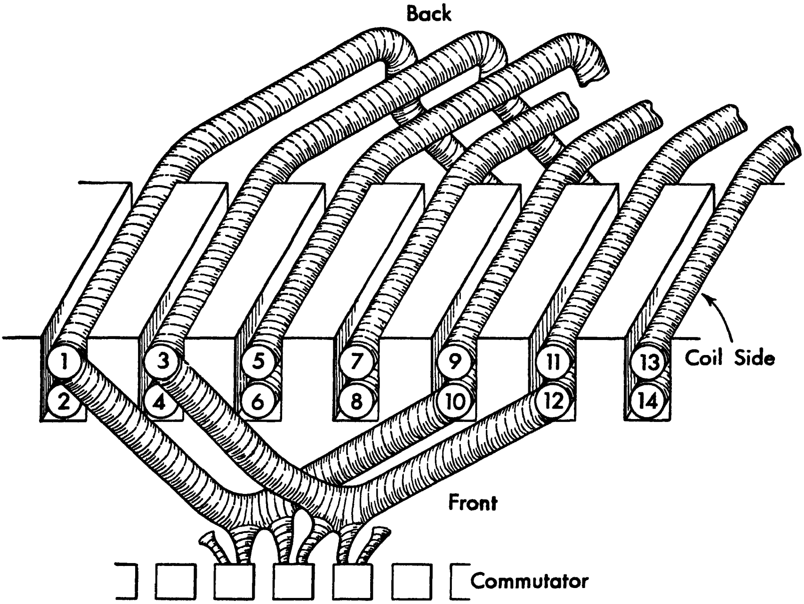


FIG. 26 Schematic representation of a typical lap winding with two coil sides in each armature slot.

those at the bottom of the slot, both the front pitch and the back pitch must be odd numbers.

If the back pitch is greater than the front pitch, the winding advances clockwise (when viewed from the commutator end) and is called a *progressive* winding. If the back pitch is less than the front pitch,

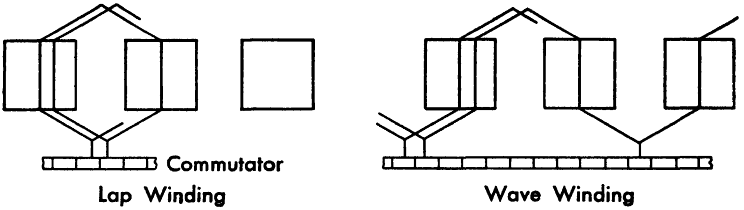


FIG. 27 Elementary representation of the two basic types of armature windings.

the winding advances counterclockwise and is called a *retrogressive* winding.

In the lap winding, it was mentioned that the coil side under one pole is connected to the coil side in a nearly corresponding position under the next adjacent pole. This second coil side is then connected back again to a coil side under the original pole. Now, if instead of connecting the second coil side back to the original pole, it was advanced forward to the next corresponding pole, it becomes a wave winding. This difference is shown in Fig. 27. In the wave winding, the next coil side is located at a considerable distance around the armature from the previous coil side.

The principal electrical feature which distinguishes the lap from the wave winding is the number of parallel electric paths through the armature. By this is meant the number of routes by which the current can travel through the armature from the positive side to the negative side of the external circuit. In the lap winding, the number of paths from one side of the circuit to the other is equal to the number of poles in the motor. In the wave winding, there are only two such paths, regardless of the number of poles. In the lap winding, the coils may be thought of as being connected in parallel, while in the wave winding they are connected in series. The terms *parallel* and *series* are sometimes used to distinguish between these two types of windings. Because there are as many parallel paths as poles in the lap winding, there must be as many sets of brushes as there are poles in the motor. In the wave-wound motor only two sets of brushes are actually necessary, regardless of the number of poles. However, in the wave-wound motor as many brushes as poles *may* be provided, in which case the brushes of like polarity are connected together.

Because of the difference in the number of parallel paths in the armature circuit, the wave winding is usually found in motors designed for high voltages and low currents, while the lap winding is more common in motors operating at lower voltages and high currents. However, there is no fixed rule for this, and either type of winding may be encountered in a given size motor.

The term *singly re-entrant* is applied to lap windings when it is possible, after starting at a given segment on the commutator, to trace a single circuit through all the armature coils and return to the starting segment. Such a circuit closes on itself after tracing all the way around the winding. When a winding is arranged in such a way that the circuit closes on itself halfway around, it is said to be *doubly re-entrant*. That is to say that one-half the coils form a closed circuit on themselves.

In the theoretically perfect motor, the air gap under each magnetic pole and the magnetic flux from each pole is equal. Practically, this condition is impossible to achieve. Variations in the air gap do exist and there are variations in the amounts of magnetic flux available to the armature under each field pole. Because of this, there are slight variations in the amount of current flowing in different sets of armature coils. This means that there will be circulating currents between brushes of like polarity. The effect of these circulating currents is to cause excessive sparking at the brushes and excessive heating of the armature coils themselves. This condition exists only in the lap winding as the series connection of the wave winding tends to automatically correct this situation. Therefore, to avoid circulating currents within the lap winding, points of equal potential are connected together. These are known as *equalizer* connections. Any stray circulating currents will then flow through these equalizer connections instead of the armature coils, thus keeping the armature in electric and magnetic balance.

The cross connections are made between points of equal potential and like magnetic polarity on the armature. Such points are physically 180 degrees apart on the four-pole motor and 120 degrees apart on a six-pole motor. The number of physical degrees is equal to 360 degrees divided by the number of pairs of magnetic poles.

It is common practice to install these equalizer connections directly back to the commutator. There are a great many different arrangements of these connections, depending upon the design of the motor. In one form, insulated rings made of thin strips of copper are placed at the rear of the commutator. Connections are made between these copper rings and the bars of the commutator at suitable points. There is usually one such ring for each pair of poles. In another form, a winding of wire replaces the copper strips.

Armature windings are subject to so many variations that it is impossible to cover them all here. There are a number of excellent texts devoted exclusively to this subject and reference should be made to them for more complete information. Such information is particularly necessary for those who have to repair or rewind armatures. But this subject is beyond the scope of this book.

CHAPTER 7 Commutation

THE current flow in a given armature coil reverses in direction as the sides of the coil pass from under one pole to the next. It is a function of the commutator to accomplish this reversal as the armature rotates. This change in direction of the current must be very rapid as the brush passes from one commutator segment to the next. Since the armature coils are wound on a magnetic core, they possess a certain amount of self-inductance which has the effect of opposing any change in current. This may be compared to the effect of inertia which tends to oppose a change in mechanical motion. The effect of self-induction is to prolong the current flow in a given direction just when it becomes necessary to make the current reversal take place as rapidly as possible. This means that a current is still flowing at the instant the brushes break contact with a given commutator segment, causing excessive sparking at the brushes. To minimize this sparking, the brushes of a motor must be shifted as will be explained presently.

It was pointed out in Chap. 1 that two distinct magnetic fields exist within a motor. It was mentioned that the motion of a motor was brought about by the reaction between these two magnetic fields. Unfortunately, these two magnetic fields introduce certain complications when they react with each other.

Figure 28(a) shows the magnetic field of the armature alone when no current flows in the field coils. Here the vertical line represents the neutral where the magnetic flux is a minimum. As shown in the figure, the magnetic flux is symmetrical, that is, it is equally balanced on each side of the armature. This magnetic field results from the current in the armature coils alone. Figure 28(b) shows the resultant magnetic field when current flows in both the armature and the field coils. This resultant magnetic field is determined by the relative strength of the two reacting fluxes. In Fig. 28(a) the magnetic neutral was also the geometric neutral, that is, halfway between the two poles. Since it is at a point where the direction of the current in the armature reverses, it is the logical location for the brushes. In Fig. 28(b), where the result of the combined magnetic fields are shown, the resultant flux is distorted and is more dense at the lower left and upper right ends of the field magnets. The direction of rotation of the armature is indicated by the arrow. The magnetic field is now distorted in a direction *opposite* to the direction of rotation. Now the magnetic neutral is no longer at the geometric neutral. The magnetic neutral has shifted backward, that is, against the direction of rotation, necessitating the shifting of the brushes backward if they are to remain at the magnetic neutral. However, because of the additional effect of the self-induction of the armature, it is necessary to set the brushes slightly behind the neutral plane shown in the figure. This backward movement of the brushes is accompanied by a further demagnetization action on the field of the motor.

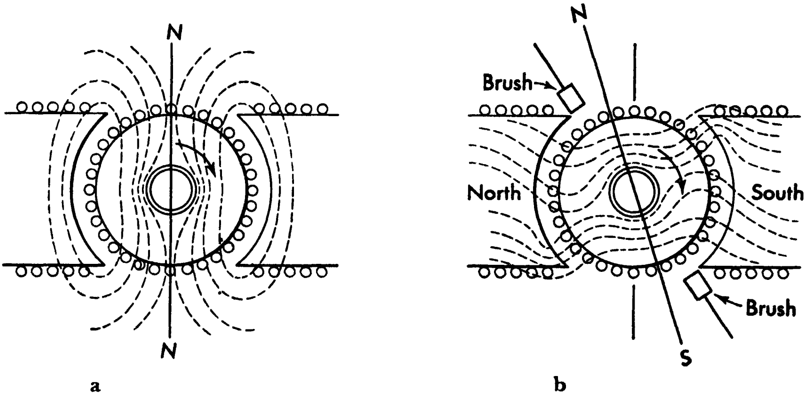


FIG. 28 The shifting of the neutral plane due to the effects of armature reaction

When the load on a motor changes, the amount of current which flows in the armature coils also changes. For each value of the armature current, the resultant magnetic field shifts slightly. Thus if the brushes are to remain in true neutral, they must be shifted for each change in load on the motor. From this it can be readily seen that the reactions between the magnetic fields within the motor become quite involved and the setting of the brushes becomes a complicated matter.

In order to overcome the effects of armature reaction in the neutral plane, and for the purpose of inducing an electromotive force in the armature coils undergoing commutation which will oppose the electromotive force of self-induction within the armature coils themselves, small auxiliary field poles are placed between the main field poles.

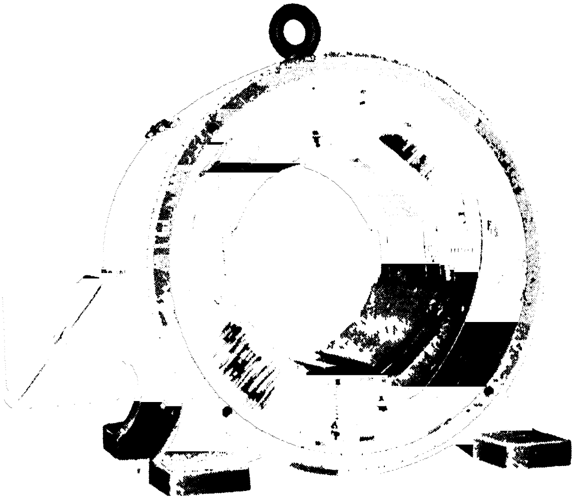


FIG. 29 Motor frame with main field and interpole windings in place (*Century Electric Co.*)

These are called *interpoles*, or *commutating*, poles. They can be seen in position in Fig. 10; in Fig. 18 an interpole is shown at the extreme left.

Figure 29 shows the position of the interpoles on a four-pole motor. By a four-pole motor, we mean one with four main poles. The interpoles are not generally considered when referring to the number of poles in a d-c motor. The polarity of the interpole shown in the figure is the same as that of the last preceding main field pole as the armature rotates. Interpoles are designed to set up a reversing magnetic field at the geometric neutral between the main field poles and to eliminate the necessity of shifting the brushes. The winding on the interpole is designed to set up a magnetic field of the proper strength to make the magnetic neutral coincide with the geometric neutral.

The windings around the interpoles are connected in series with the armature circuit. When the load on the motor changes, causing the amount of current flowing in the armature circuit to change, the field strength of the interpoles changes correspondingly. Thus the magnetic neutral remains in a fixed position regardless of the changes in the normal load on the motor.

There are usually as many interpoles as there are main poles, but in some motors only half as many interpoles are provided. In such motors, the interpoles are designed to produce double the amount of flux to be cut by one coil side of the armature winding instead of a single flux to be cut by both coil sides. Thus it makes little practical difference within a given armature coil as to whether one side cuts a double flux or each side cuts a single flux. It should be noted that the effect of the interpole is to overcome the armature reaction in the immediate area under the pole only, and that field distortion is still present in other parts of the motor. This can be greatly reduced by the use of compensating windings across the face of the main field poles. Such windings are costly and are limited in use to very large motors and certain highly specialized applications. Slots in the main field poles in which the compensating windings are placed can be seen in Fig. 10. The interpole and compensating windings together make the effects of armature reaction harmless.

Since the windings of the interpoles are part of the armature circuit, the motor may be reversed by reversing either the armature circuit or the field circuit (but not both), and the proper relationship of interpole polarity to main pole polarity will be maintained.

When reconnecting interpole motors which have been taken out of service, it is of special importance to check the polarity of the interpole windings. This checking is necessary due to the fact that the interpoles may be improperly connected when the normal direction of rotation is in doubt. The correct sequence requires that the polarity of the interpole be the same as that of the last preceding pole as the armature rotates. Hence the direction of rotation must be known in order to properly connect the interpole windings.

It should also be noted in connection with the subject of armature reaction, that as the motor armature rotates and the commutator segments pass under the brushes, certain armature coils undergoing commutation are momentarily short circuited through the brushes. The electric resistance of the brush material helps reduce the short-circuit current and thus assist in the commutation process. This problem will be considered further in the chapter on brushes.

CHAPTER 8 Commutator Care

The fundamental requirement for successful commutation is continuous and intimate contact between the commutator surface and the brushes. To maintain this contact, the commutator surface must be kept in proper condition. The commutator should be inspected at regular intervals so that surface faults can be detected in the early stages of formation.

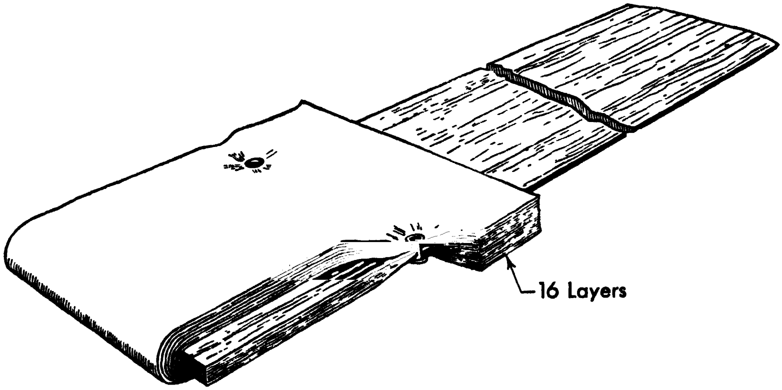


FIG. 30 Shop made canvas commutator cleaner (*Copyright 1940 National Carbon Company, Inc.*)

If the commutator is mechanically true, its surface may be cleaned with a piece of dry canvas which has been folded a number of times to form a pad and then securely fastened over the end of a long flat piece of wood. This is shown in Fig. 30. There should be about 16 layers of material in the pad. It should be held firmly against the commutator surface, as shown in Fig. 31, while the motor operates at normal speed. This imparts a slight polish to the surface as well as cleaning it.

Foreign deposits may be removed from the commutator surface by sandpapering. The sandpaper should be fine grain to avoid making deep scratches in the copper surface. The sandpaper is attached to a wooden block which has the same curvature as the commutator. Emery paper or emery cloth should never be used for this purpose, as emery is an electric conductor and particles which become imbedded between the commutator segments are likely to cause short circuits.

FIG. 31 Canvas commutator cleaner in use. (*Copyright 1946 National Carbon Company, Inc*)

When small flat spots are present on the commutator surface, it should be *stoned* rather than sandpapered. The stone presents a rigid surface to the commutator It should, of course, have the same curvature as the commutator and have a span of contact greater than the broadest flat spot. Commutator stones of the correct size and suitable abrasive material are made especially for this purpose. They are provided with handles for ease of manipulation and are available in several grades ranging from very coarse to very fine. A medium grade is generally used in order to keep the amount of copper removed to a minimum. The stone is firmly applied to the commutator surface by hand while the motor operates at its normal speed.

If the commutator is "out of round," that is, not mechanically true, neither sandpapering nor stoning will eliminate the eccentricity. In the case of small motors, the entire armature should be removed, placed in a lathe, and the commutator trued by taking a light cut from its surface. A diamond-pointed steel tool is generally used. The point of the tool should be rounded sufficiently so that the cuts will overlap and not leave a rough thread on the commutator surface. With large motors where considerable labor would be involved in removing the armature, a special grinding rig designed for mounting a stationary stone on the motor brush rigging is available. The stone is held in a carriage which may be moved back and forth over the width of the commutator surface. It is also equipped with a feed mechanism so that the stone can be fed against the surface as it wears. Grinding should be done with the motor operating in its own bearings at rated speed. To prevent copper particles from entering the windings during this operation, the grinding rig is often equipped with a vacuum cleaner to remove the dust as it forms.

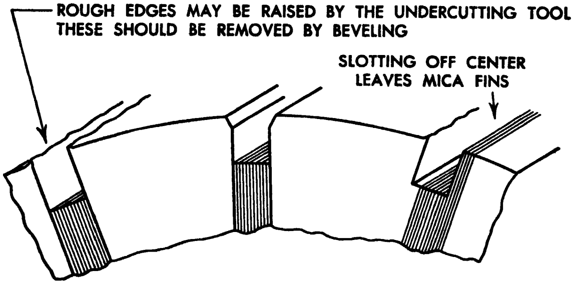

ROUGH EDGES MAY BE RAISED BY THE UNDERCUTTING TOOL THESE SHOULD BE REMOVED BY BEVELING
SLOTTING OFF CENTER LEAVES MICA FINS

FIG. 32 Commutator undercut with U type slots. (*Copyright 1946 National Carbon Company, Inc.*)

The use of a grinding rig for truing a commutator is generally preferred to lathe turning, as less copper is removed and the face of each individual commutator segment will have a truer curvature. Another reason for preferring the use of a grinding rig is that the armature turns on its own bearings during the truing operation. Unless the proper equipment is at hand, it is better to send the armature to a reputable service shop than to attempt a makeshift job.

It has previously been mentioned that in the construction of the commutator, mica is used as the insulating material between bar segments. Since copper normally wears away more easily than does mica, there is a tendency for the mica to protrude above the surface of the commutator. This condition is popularly known as *high mica.* It prevents the brush from making proper contact with the surface of the copper segments of the commutator. To correct this, the mica is undercut. This means that the mica is cut down below the copper surface of the commutator. Figures 32 and 33 show enlarged sections of a commutator with the mica undercut. Figure 32 illustrates U-shaped slots, whereas the slots in Fig. 33 are V-shaped. Both forms are widely used.

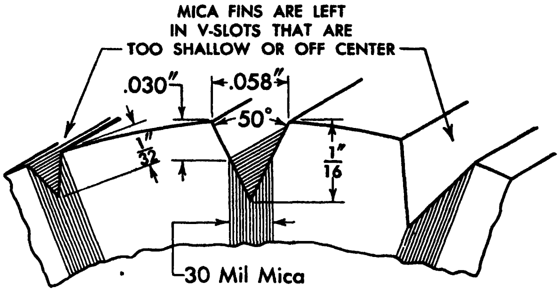

MICA FINS ARE LEFT IN V-SLOTS THAT ARE TOO SHALLOW OR OFF CENTER
.030"
.058"
50°
1/32"
1/16"
30 Mil Mica

FIG. 33 Commutator undercut with V type slots. (*Copyright 1946 National Carbon Company, Inc.*)

The operation of undercutting the mica is sometimes called commutator slotting. Many tools are now on the market, some hand operated and some motor driven, by means of which commutators can be properly undercut. Many maintenance men use a piece of hack saw blade mounted in a handle consisting of two narrow wooden blocks bolted together. Such a tool works very well as long as the blade is sharp. A dull blade tends to drag the mica out in tiny chunks, causing the remaining mica in the slot to check and crack.

The top of the mica between slots, after undercutting, should be about $\frac{1}{16}$ inch below the commutator surface. The undercutting may leave the slot in the form of a U or a V as shown in Figs. 32 and 33. There are many arguments in favor of each form but either works very well under normal operating conditions.

The edges of the commutator bars are usually beveled to remove the burrs formed during grinding and to eliminate the sharp edge at the side of the commutator bar which moves under the brush.

Upon completion of grinding and undercutting, the commutator surface should be burnished to remove the last traces of roughness. A hard maple block is recommended for this purpose. It is applied with the end grain contacting the commutator surface. A single block may be held against the commutator surface by hand or a number of maple blocks of proper size may be inserted in the brush holders to replace the brushes. Enough brushes must remain on the commutator to permit operating the motor at normal speed unless it can be so driven from a separate source of power. For effective burnishing action, the blocks should be applied with considerable pressure, and care should be taken that the commutator does not become excessively hot.

Grooving of the commutator in normal operation is often caused by the use of brushes having too high an abrasive quality or by incorrect staggering of brushes. This condition can be helped by providing a small amount of end play in the armature so that the brushes do not always make contact in the identical spot. Brush materials and brush staggering are discussed in the next chapter.

CHAPTER 9 Motor Brushes

ALTHOUGH much research has been done on the analysis of motor brushes and brush operation in the d-c motor, comparatively little literature on this subject is readily available. Since brushes are often considered the most troublesome part of the d-c motor, they have long been looked upon as a necessary evil. A comprehensive understanding of the brush function will do a great deal toward eliminating the difficulties which are commonly associated with motor brushes.

Brushes actually have three distinct functions to perform. First, they must carry the load current to the rotating armature; second, they assist in reducing armature reaction associated with the commutation process; and, lastly, they must maintain intimate mechanical contact with a rapidly moving surface with a minimum amount of wear to that surface. No single brush material yet developed will fulfill all of these requirements under all conditions of motor operation. Compromises are necessary, but, nevertheless, there are brush materials available which will give eminently satisfactory results under a given operating condition.

It is generally assumed that a well fitting and polished brush makes a nearly perfect contact with the commutator. Actually, this is not the case. The surface of the brush and the commutator are seldom of identical curvature. Because of the play of the brush in its holder and the vibration and yielding of the supporting assembly, the brush face may have a slightly longer radius of curvature than the commutator. This greatly reduces the area of contact. As a result, a lesser area than the whole brush face must carry the entire load current. This area is constantly shifting and changing due to mechanical vibration and wear of the brush itself. When several brushes of the same polarity are connected together, as in most commercial motors, there is a constant variation in the proportion of load current which each brush carries. This has a tendency to cause uneven wear of the brushes which in turn only aggravates the matter. High-current densities in small spots on the brush faces cause burning and sparking. This makes the situation even worse.

While there is no known way of overcoming these difficulties completely, variations of current density can be greatly reduced if all brushes are of identical material and under identical mechanical pressure on the commutator. All the brushes should fit properly in their holders and the holders themselves must be in good mechanical condition. Often, variations which are not readily observed lead to trouble in a comparatively short time.

Brush materials are of four general types:

1. Carbon-graphite
2. Graphite
3. Electrographic
4. Metal graphite

Within each of these four general types are wide variations of both physical and electrical characteristics. The physical characteristics concern such matters as mechanical strength, coefficient of friction, hardness, and abrasiveness. The electrical characteristics are principally specific resistance and contact voltage drop. Each brush manufacturer offers many grades within each general type. This means that there are actually hundreds of grades of carbon brush material available. While this multitude of brush grades may seem to complicate the situation, actually they simplify it since it makes readily available the exact grade needed for a specific application.

Broadly speaking, brushes of the carbon graphite group are best suited to slow speed reversible motors, crane motors, elevator motors, fractional horsepower motors, and railway motors. Graphite brushes are generally used for high-speed motors and for some types of fractional horsepower motors where quiet operation is desired. The electrographic grades find use in heavy-duty high-speed equipment and general purpose industrial motors. This is probably the most widely used of all grades. The metal graphite brush is used in low voltage service where current densities are likely to be high. They are more widely used in generators and alternating current equipment than in direct current motors.

Since the brush rides on the commutator, the commutator surface also plays an important part in the commutation process. A raw copper surface on the commutator does not lend itself to good brush performance. Some oxidation is definitely necessary. The development of an oxide surface film will give the commutator a color which varies from light straw to chocolate or almost black. The surface should, of course, be clean and smooth and have a good polish. This oxide coating should not be confused with dirt and foreign material. It is an essential film necessary for good commutation. The composition of the brush material may either build up this oxide surface film or cause it to break down completely. It is sometimes beneficial to use a film-removing brush material when the motor operates in atmospheres which cause excessive oxidation. Such brushes are popularly called cleaning brushes.

The voltage drop between the face of the brush and the commutator surface is known as the *contact drop*. That a high-contact drop aids in reducing the short-circuiting currents in the armature coils has already been mentioned. This contact drop varies from slightly under 1 volt to over 2 volts, depending on the brush material. This is considerably higher than that between two pieces of copper or even between two pieces of carbon. In view of recent research, it is doubtful if the matter of contact drop is as important to good commutation as it had been considered in the past. One reason for this is, perhaps, because the short-circuit currents have been greatly reduced in the modern well-designed d-c motor.

Another important factor which must be taken into consideration is the current-carrying capacity of the brush material. A metal-graphite material will handle as high as 150 amperes per square inch of brush surface, whereas a fine-texture carbon-graphite material will only carry 35 amperes per square inch. The more common electrographic grades range from 60 to 70 amperes per square inch. When the current-carrying capacity of the material is exceeded, the brush will heat. In this connection, it should be noted that the conditions under which the motor operates must be considered. At times, the current that can be carried by the brush may be either higher or lower than the rated normal capacity. Motors that operate intermittently may have brushes which often carry considerably more current than the manufacturers rating. In general, small brushes can carry higher current densities than larger ones. A great deal depends on the design of the motor itself, particularly its ventilation.

The matter of prescribing the correct brush material for a given motor rests with the motor manufacturer. His recommendations will usually give the best results under average conditions. However, for specific applications and under adverse operating atmospheres, it may be necessary to depart from the recommended grade. Should this become necessary, consideration should be given to the opinion of a technical brush expert. In making his recommendations, he will give consideration to such factors as maintaining the proper film on the commutator surface, the density of the current carried by the brush, and its ability to give satisfactory commutation service without undue sparking. Even experts often find it necessary to resort to a trial-and-error method in difficult cases. It should not be assumed from what has been said that all commutation troubles are caused by the wrong grade of brush material. Incorrect brush materials are only one of the many causes of commutation difficulties.

Since brushes are expendable, they must be replaced at regular intervals. For best results, *all* the brushes on a given motor should be replaced at the same time. It is poor economy to allow a brush to wear down too far. No fixed rule can be given for this as so many factors are involved, but, in general, it is good practice to renew brushes when they have worn about two-thirds to three-quarters of their original length. Because brushes must be replaced regularly, it is important to know how to order brushes so that the correct grade, size, shape, and type will be supplied. Brush terminology has been standardized by the National Electrical Manufacturers Association and their definitions have been generally accepted by the entire carbon brush industry. To facilitate intelligent ordering, these standard definitions will be given in detail. Most brush makers wll supply printed order forms so that the required information may be tabulated in orderly fashion.

The number (if any) stamped on the brush itself usually refers to the grade of the carbon only. This number gives no indication as to the brush size, shape, type, etc. Certain motor manufacturers stamp the complete catalog or style number on the brush, but since this is the exception rather than the rule, it can not be depended upon. Such catalog numbers are rather long (six or more figures) while those numbers indicating the grade of the brush material are considerably shorter. At all events, any numbers or marks which appear on the brush itself should always be given when ordering in addition to the complete

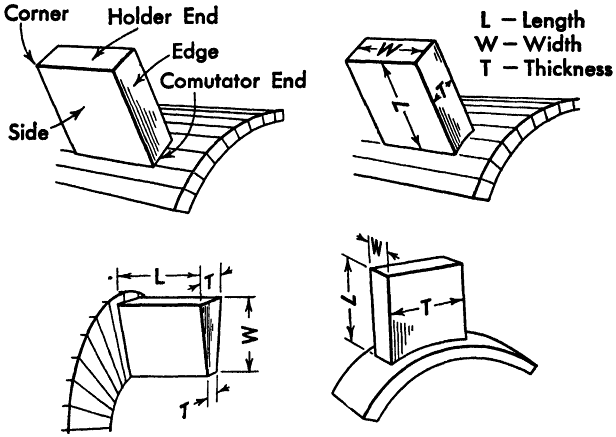


FIG. 34 National Electrical Manufacturers Association standard for designating brush dimensions. (*Copyright 1946 National Carbon Company, Inc.*)

descriptive details. If no number appears and if there is any doubt at all as to the exact grade of brush material, it is best to submit an old brush as a sample so that the supplier can match the grade of carbon.

Since each brush maker has his own system of grading carbon brush materials, his trade mark is often stamped directly on the brush along with a number or symbol representing his grade designation. Here again there are exceptions for all brush makers do not manufacture the carbon material. These brush makers purchase the material in large slabs or plates and cut it as required. In such cases there is no way of identifying the original material maker. It is helpful to be able to identify the maker's mark when it does appear on the brush, and it is suggested that the motor user familiarize himself with at least the more common brush trade marks.

After the grade of material has been determined, the brush dimensions should be given. The over-all dimensions indicating the size of rectangular brushes should always be given in the following order: length, width, and thickness. The length of a brush is its maximum

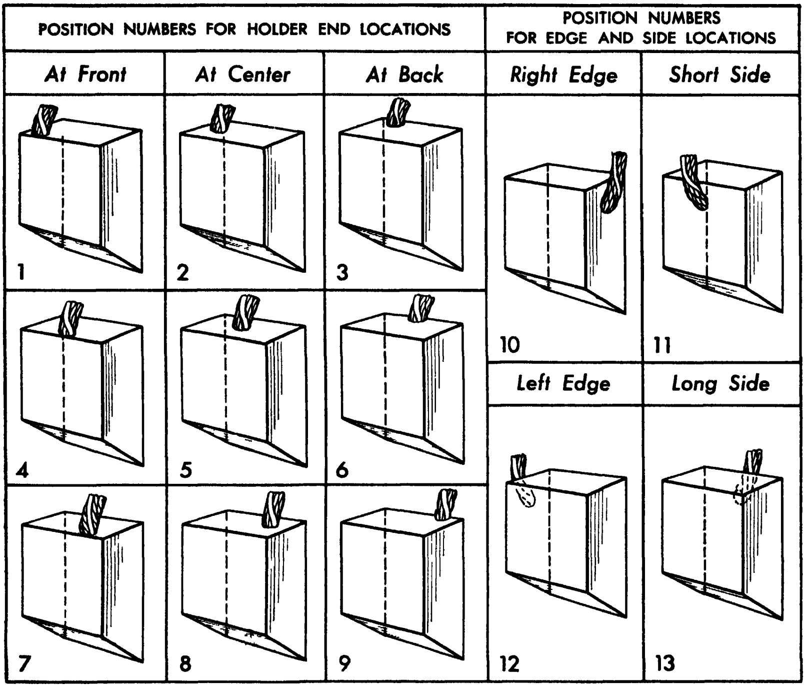
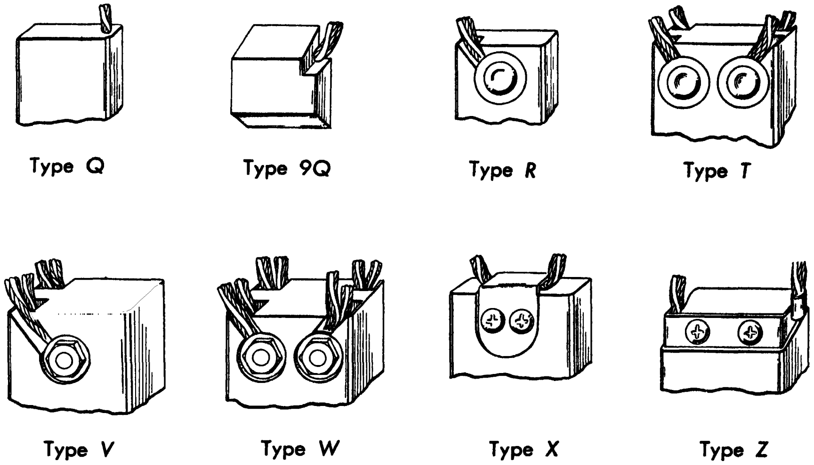

POSITION NUMBERS FOR HOLDER END LOCATIONS
POSITION NUMBERS FOR EDGE AND SIDE LOCATIONS
At Front
At Center
At Back
Right Edge
Short Side
1
2
3
10
11
Left Edge
Long Side
4
5
6
7
8
9
12
13

FIG. 35 National Electrical Manufacturers Association standard for designating the point of attachment of the brush shunt. (*Copyright 1946 National Carbon Company, Inc.*)

over-all dimension in the direction which the brush feeds to the commutator. The width of a brush is the dimension at right angles to the length along the direction of the commutator bar. The thickness of a brush is the dimension at right angles to the length in the direction of rotation. These dimensions are illustrated in Fig. 34, where a number of differently shaped brushes are shown.

Brushes are usually provided with a short piece of flexible copper cable to form a shunt or by-pass for the current between the brush and its holder. This is called a *brush shunt* or, more popularly, the "pigtail." This flexible shunt is necessary to provide a current path which is not affected by the movement of the brush or the clearance between the brush and its holder. To simplify the designation of the shunt position, a numerical system has been adopted by the brush industry which is shown in Fig. 35. The number shown at the lower left of each brush in the illustration is all that is necessary to designate the desired shunt location.

Five general types of shunt connections are popularly used. By the term *shunt connection* is meant the method by which the shunt is secured to the brush material These are the embedded, the riveted, the bolted,


Type Q

Type 9Q

Type *R*

Type *T*

Type *V*

Type *W*

Type *X*

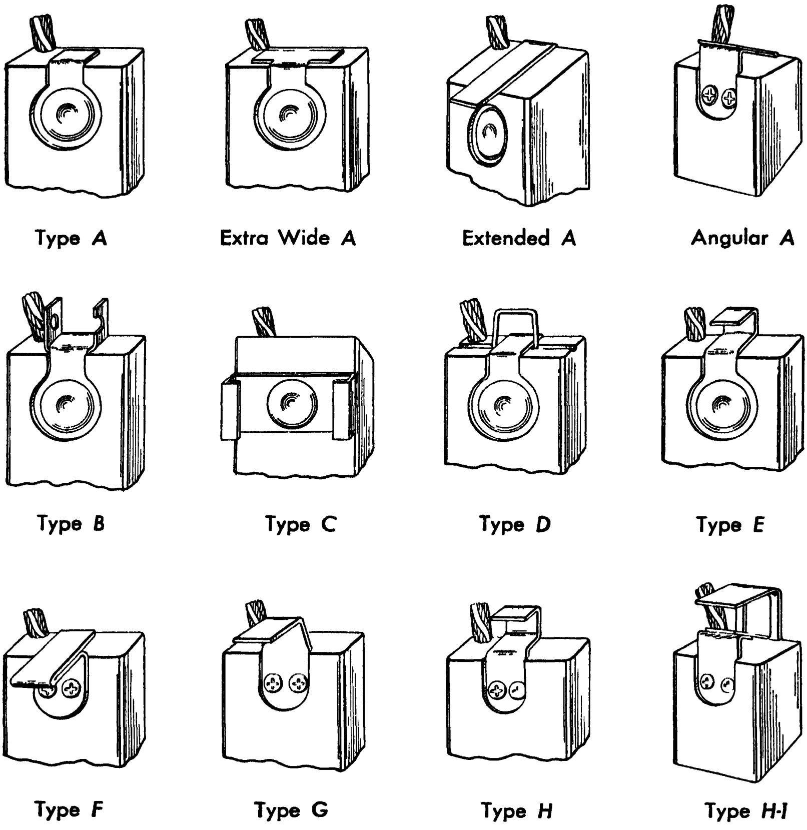
Type *Z*

FIG. 36 National Electrical Manufacturers Association standard for designating method of attachment of the brush shunt. (*Copyright 1946 National Carbon Company, Inc.*)

the saddle, and the plate types. Within these five general types are several special types. Each type has been given a standard *letter* designation. Letters toward the end of the alphabet have been selected for this purpose.

Type *M* indicates a connection in which the shunt is molded into the brush at the time of its manufacture. Type *P* designates a shunt which is wedged into a hole in the brush by means of a screw or driven pin. In type *Q* a hole is drilled into the brush and the shunt cemented in with a special conductive material. Type *R* is a riveted connection. When two rivets are used, the shunt connection is known as type *T*. Types *V* and *W* are bolted, while type *X* is known as the saddle type. Another type known as *Z* fastens the shunt to a metal plate which in turn is riveted to the brush. Illustrations of typical shunt connections are shown in Fig. 36.

The length of a brush shunt is defined as the distance from the top end of the brush to the center of the hole (or slot) in the terminal end of the shunt. This length varies with the type of the brush holder and must always be stated when brushes are ordered. The type of the terminal to be placed on the end of the shunt should also be mentioned, as various types of brush holders require different terminals. These terminals are usually crimped on to the end of the shunt.



Type *A* Extra Wide *A* Extended *A* Angular *A*

Type *B* Type *C* Type *D* Type *E*

Type *F* Type *G* Type *H* Type *H-1*

FIG. *37* National Electrical Manufacturers Association standard for designating hammer plates and lifting clips on carbon brushes. (*Copyright 1946 National Carbon Company, Inc.*)

Brushes may have bevels at either the top or the bottom (the face) or both. Bevels must be accurately specified when ordering brushes for they usually call for special machine work. It is customary to state the bevel in angular degrees measured from the horizontal.

It is frequently desirable to equip brushes with hammer clips to prevent the brush spring pressure from wearing grooves or notches in the top end of the brush. This interferes with the free movement of the brush in its holder. Lifting clips are sometimes provided for ease of lifting brushes clear of the commutator. Both hammer and lifting clips have been given standard letter designations taken from the beginning of the alphabet. These are shown in Fig. 37.

In some special applications it is advantageous to use a double brush. This is actually two separate narrow brushes in place of a single very thick brush. A hammer plate similar to the extended *A* type, shown in Fig. 37, attached to one of the brushes distributes the spring pressure over both. Each brush has its own shunt and both shunts usually end in a single common terminal. Both brushes are installed as a unit in the conventional brush holder on the motor. The double brush gives better contact with the commutator surface and tends to reduce vibration and uneven wear.

From what has been said about the ordering of brushes, it can readily be seen that it is impossible for a supply house to stock all sizes, types, and styles of motor brushes. Except for the most commonly used brushes, it is customary to make brushes to order. This takes time and motor users are strongly urged to keep at least one full set of brushes for each motor on hand at all times. When these brushes are installed, another complete set should be immediately ordered. One of the old worn brushes should accompany the order as a sample. In this way, shutdowns because of brush trouble can be reduced to a minimum.

CHAPTER 10 Installing and Maintaining Brushes

INSTALLING brushes in a motor is a simple operation, yet many difficulties with brushes have their origin in improper installation. The brush holders themselves play an important part, for it is essential that they be properly spaced and aligned. If a brush holder shows indication of burning, corrosion, or mechanical damage, it should be replaced. A damaged brush holder may prevent the free movement of the brushes as they ride on the commutator, or it may be so loose or worn that the brushes wobble or vibrate. All of these factors have a direct influence on commutation.

Accurate spacing of the brushes around the commutator is very important. Lack of uniform spacing causes circulating currents to flow between brushes of like polarity. It is all too often assumed that the brush holder spacing is properly set at the factory and that further checking is unnecessary. It should be remembered that many things can happen to a motor after it leaves the factory and still more things may happen during and after the motor installation which may affect the brush-holder spacing.

One way to check the brush-holder setting is to wrap a strip of paper completely around the commutator and with a sharp pencil make a line to indicate the toe line of each brush. The paper is then removed and the distance between marks carefully measured. Any unevenness should be corrected by adjusting the proper brush holders.

There should be a clearance of about ⅛ inch between the bottom of the brush holder and the surface of the commutator. The exact amount of clearance depends to some extent on the type of brush holders on the machine. The manufacturer's instructions usually cover this point and the clearance should be checked every time new brushes are installed.

Brushes should also be perfectly aligned with the commutator bars. If one edge of a brush is set exactly on the edge of a commutator segment, any lack of alignment will show up immediately. Prompt steps should be taken to correct any unalignment, for it may ultimately lead to commutation difficulties.

The brush must approach the commutator at the proper angle. This angle may be leading, trailing, or radial (no angle). Factors entering into the brush angle are commutator surface speed, direction of rotation, and whether or not the motor is frequently reversed. This angle may be anything from 20 degrees to 40 degrees, depending on the design of the machine. The correct angle is usually specified by the manufacturer and set at the factory. Figure 38 shows two brush yokes with the brush holders set at typical angles.

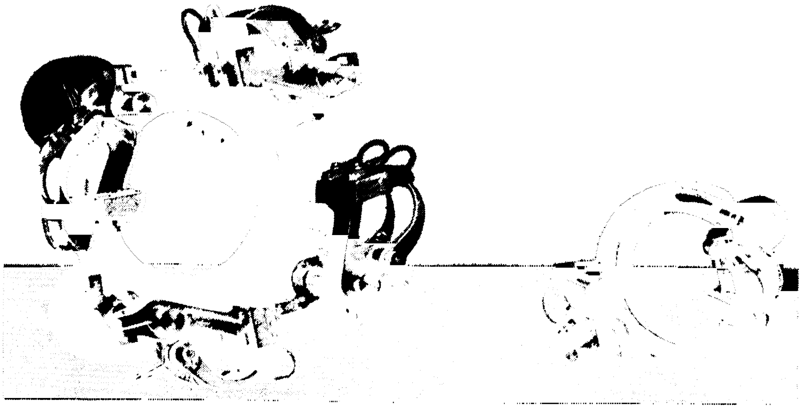


FIG. 38 Brush yoke with brush holders The slots seen in the yoke are essential for shifting the position of the brush assembly. (*Allis-Chalmers Mfg. Co.*)

There are two forms of brush holders in popular use. These are the *box* type and the *reaction* type. They are shown in Fig. 39. An inspection of this illustration will make the difference between them clear.

Brushes must be set on the commutator at the point where the armature counter electromotive force reverses its direction. This is known as the *neutral point*. In most instances, the brushes have been carefully set at neutral before leaving the factory. However, it is important to know how to make this setting if it has been disturbed.

The manufacturer may mark two armature slots one pole pitch apart, or as nearly so as possible if a whole number of slots per pole is not used. The commutator segments connected to the top conductors in one slot and the bottom conductors in the other slot are marked by symbols (usually *T* for top and *B* for bottom) stamped into the ends of the bar segments. When the armature is turned so that the marked slots are directly under the center of two commutating poles (interpoles) or halfway between two main field poles, the neutral will then be at the exact center of the group of marked commutator segments

There are a number of electrical methods for determining the exact location of the no-load neutral point. The following methods are suggested in the "Test Code for Direct Current Machines" published by the American Institute of Electrical Engineers.

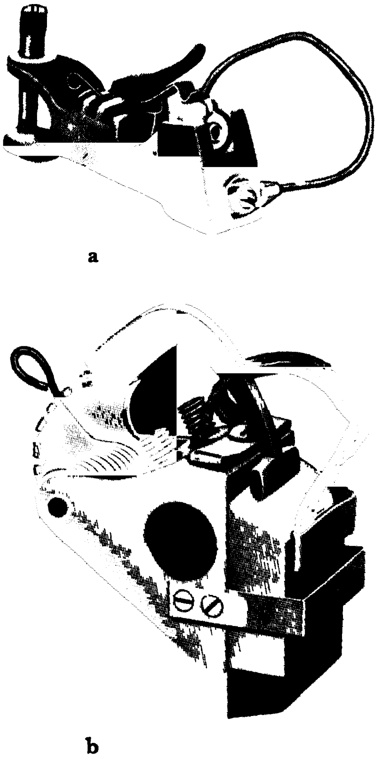


FIG. 39 Typical brush holders. (*a*) box type. (*b*) reaction type. (*Copyright 1946 National Carbon Company, Inc.*)

(a) *Test by Moving Armature Through Small Angle* (*Kick Method*)

The no-load neutral may be located by observing the voltage induced in the stationary armature winding by alternately establishing and destroying a flux in the main poles. The usual procedure is as follows: Raise all brushes. Select two commutator segments spaced one pole pitch apart (total segments divided by number of poles). In case the bars per pole pitch is not an integral number two sets of readings should be taken, one with a pitch of the next integral number below full pitch and one with the next higher. An average between the two will represent the readings sought. Connect to these segments or to their necks or leads a 0.5–1.5–15 scale d-c voltmeter. The voltmeter lead contacts with the commutator must always be one pole pitch apart and must remain on the same commutator segments. Use the 15-volt scale until voltages fall within the range of the lower scales. Employ a quick-break auxiliary jaw knife switch to insure a more uniform rate of interruption of current.

Arrange to excite the main field from a separate d-c source with not more than 20 per cent of normal current which may be established and interrupted by means of the quick-break switch.

For factional horsepower motors uses 50 per cent of normal current for 230 volt and 75 per cent for 110 volt motors. Furthermore, for fractional horsepower motors it is desirable to use brushes beveled to a narrow surface in the center of the brush for best results.

On opening the switch the "decaying" field flux will induce a voltage in the armature coils between the selected segments and this kick may be read on the voltmeter.

The armature should be turned a few degrees at a time, with the voltmeter always connected to the same segments and the observation repeated until a position is found where a change in field produces no indication even in the 0.5-volt circuit of the voltmeter. When this occurs, the portion of the winding between the voltmeter leads is equally or symmetrically located under the poles. It is the position where the voltage by transformer action is a minimum and the voltage due to motion would be a maximum.

(b) *Test with Armature Stationary (Kick Method)*

If the armature cannot be rotated readily the voltmeter leads may be moved around the commutator. In this case it is desirable, if possible, to determine the neutral for several slightly different armature positions and take the average of such neutrals.

The neutral point on the commutator is then at the two selected segments. The centers of the brushes should be set on these points. In cases where the bars per pole pitch is not an integral number the voltmeter leads must still remain a pole pitch apart and a number of readings should be taken on either side of the point where the kick reverses. The point at which a curve plotted from these readings passes through zero will indicate the no-load neutral position.

A further refinement may be made by locating a segment mica on one of these points and reading the voltage kick between the first two segments on either side of this mica. When the selected segment mica is exactly on the no-load neutral, the kick between these two pairs of segments will be equal in magnitude and of opposite polarity.

(c) *Reverse Rotation Method*

Reversible motors may have their neutral located by this method. Operate the motor at constant voltage, constant field current, and constant load. The fit between brush face and commutator must be good. Measure the rotational speed for both directions of rotation. When the brushes are located on the neutral the rotational speed should be the same in either direction. The machine should be run preferably at full-load, but the setting may be made at no-load. This test for adjustable speed motors should be made at maximum speed.

Although this method is suitable for any size machine it is particularly applicable to fractional horsepower motors because the accuracy is not influenced by dead coils or any other irregularity in the armature winding. For fractional horsepower motors it is recommended that this test be made at full-load and with brushes beveled to a narrow surface in the center.

(d) *Zero Torque Method (No-Load Neutral)*

This method is based on the fact that zero torque will be generated when the brushes are located on the no-load neutral and current is passed through the armature and commutating field with the main field unexcited and the residual magnetism reduced to zero.

This method is best suited for small or medium-sized machines.

The procedure is as follows: Disconnect the main field coils, shunt or series or both. Set the brushes by inspection roughly on neutral. Pass 75 per cent to 100 per cent current through the armature and commutating field coils. If the brushes are sufficiently off neutral, the armature will rotate in the same direction as the brushes are displaced from the neutral. Shift the brushes in the reverse direction until rotation ceases, and mark their position. Continue moving the brushes in the same direction until the armature rotates in this reverse direction. Then reverse the brush movement until rotation ceases and mark this new brush position. The neutral is midway between these positions.

The neutral may be further checked by noting the torque required to rotate the armature in either direction while passing current through it and the commutating field. These torques will be equal when the brushes are exactly on the neutral.

A good fit between brush face and commutator is essential to this method.

(e) *Voltmeter Method (No-Load Neutral)* (Not applicable to fractional horsepower motors.)

This method is based on measuring the voltage generated in successive armature coils as they pass a fixed point. The procedure is as follows: Set the brushes approximately on neutral by inspection. Attach to one of the brush holders or to the brush gear an insulated support or guide for two carbon pencils or narrow brushes which should be spaced apart by a small distance, approximately the pitch of a commutator segment.

These two pencil points should be equidistant from the exact center of the main brush contact arc.

A guide block of fiber or wood provided with properly spaced guide holes for the pencils may be used. Or a guide may be made of a fiber strip tied to and stretched between the two brush groups on either side of the one at which measurement of voltage is to be made. The strip should rest on the surface of the commutator at the outer end of the selected brush group. Two holes spaced and located as above should be made in the strip to serve as guides for the pencils.

An 0.5–1.5–15 scale d-c voltmeter should be connected to the two pencils which should be inserted in the guide. They are usually held in by hand if the machine voltage is 300 or less.

Then operate the machine without load at normal speed and voltage and shift the brushes until zero voltage is induced in the armature coils passing under the pencils. The point midway between the two pencils is then on the no-load neutral. The first readings should be taken on the 15-volt scale. Use the lower scales as the voltage falls within their range.

(f) *Running Commutating-Pole Method* (Not applicable to fractional horsepower motors.)

All brushes are raised and a sharply pointed brush beveled to the center of the brush is placed in each arm. The residual magnetism of the main poles is reduced to zero, and with the machine operated at rated speed, from 2 per cent to 4 per cent of rated current is circulated in the commutating-pole field (and compensating field winding if used). The rocker ring is then shifted until no voltage is produced from the armature as measured between brush arms. The neutral point is then at the points of the beveled brushes and the regular brushes are inserted and the rocker ring locked in position so that the center of the brush contact arm on the commutator corresponds to the points of the beveled brushes. This is a very accurate method of giving a neutral point and is satisfactory for both no-load and load neutral as it includes the effect of the commutating field.

(g) *Final Operating Check*

The final best brush position for good commutation and the desired voltage or speed characteristics of generators or motors, respectively, must finally be determined by observation of the machines under load.

Over a period of time, brushes tend to wear grooves on the surface of the commutator. While modern brush materials are relatively nonabrasive, it is still customary to stagger the brushes across the bar length of the commutator. This is to keep commutator wear at a minimum. The staggering should be arranged so that brushes of the same polarity do not track each other. In this way any action between brush face and commutator under brushes of one polarity will be neutralized by the action under brushes of the opposite polarity. The reason for this is that the character of the commutator surface film developed under brushes of positive polarity is not the same as that under negative polarity. Figure 40 shows the correct method of staggering brushes. Note particularly the polarity of the brush rows as indicated in the figure.

A new set of brushes must be fitted so that the curvature of the brush face is the same as that of the commutator surface. This is accomplished by the use of a medium grade of sandpaper or by specially prepared brush seating stones.

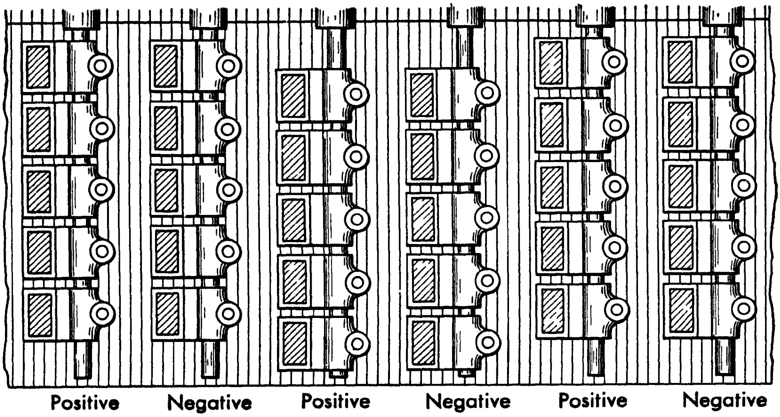


FIG. 40 Correct method of staggering brushes. (*Copyright 1946 National Carbon Company, Inc.*)

To sand a brush in, as the operation is called, the brushes are lifted and a long strip of medium sandpaper placed on the commutator surface. The brushes are then restored to their normal operation position and the sandpaper pulled under the brushes in the direction of the machine's rotation. Each time the sandpaper is pulled, the brushes are lifted while the sandpaper is drawn back to its original position for another pull. This operation is continued until the face of the brush makes a good fit with the commutator surface. The strip of sandpaper must be kept in close contact with the commutator during the sanding pull, otherwise it tends to round off the edges of the brushes.

When using a prepared brush seating stone, the motor is operated while the stone is held firmly against the commutator surface directly behind the brush. The fine particles worn away from the stone are carried under the brush face and grind the brush to an exact fit. With a stone of the proper composition, there is little wear on the commutator surface.

After the brushes are seated, either by sanding or stoning, the dust from the operation should be blown out of the machine. Should any grit remain, it may cause excessive wear or scratching of the commutator surface.

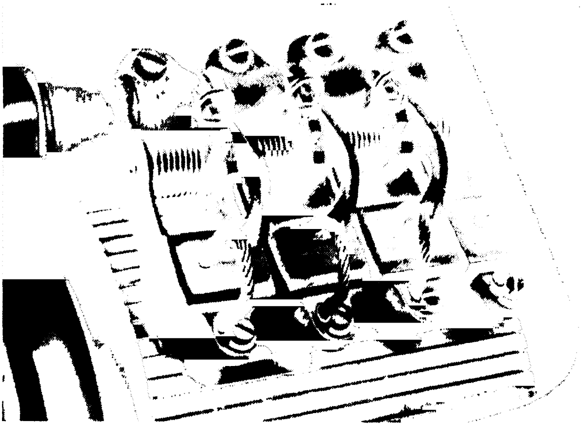


FIG. 41 Typical motor brush rigging. (*Century Electric Co.*)

After a new set of brushes have been installed and properly seated, the brush spring tension should be checked. Most brush holders are provided with means to adjust the spring tension. In Fig. 41 the brush spring mechanism is clearly shown. The brush spring pressure should be approximately two or two and one-half pounds per square inch. It can be measured with a spring balance. The hook of the spring balance is attached to the brush and the reading taken just as the brush is lifted from the commutator surface. To obtain a reasonably accurate reading, the brush should move freely in its holder and the pull made in the direction of normal brush movement. The pressure should be approximately the same on all brushes in a given motor. Incorrect brush pressure may cause excessive wear on both the brushes and commutator. It is also often the cause of excessive sparking and heating.

A brief summary of brush troubles appears in Table III. In the interests of simplicity, only the more common everyday troubles are listed.

It is assumed that the motor is properly wound and in otherwise good condition. It should be remembered that while many of the troubles of the d-c motor have their origin in brush difficulties, they are by no means to blame for all unsatisfactory motor performance.

TABLE III Brush Trouble Summary

Symptom	Possible Cause
Excessive sparking	Commutator surface in bad condition Incorrect spring pressure Brushes too short Motor overloaded Short circuit in armature Wrong grade of brush material Brushes bind in holder Brush position incorrectly set Interpoles not properly adjusted
Burned streaks on brush face	Brushes in wrong position Interpoles improperly adjusted Brush thickness incorrect
Flashover at brushes	High bar to bar commutator voltage Motor overloaded Heavy sudden load surge on motor Commutator dirty Bad atmospheric conditions
Glowing at brush face	High mica on commutator Interpoles not properly adjusted Motor overloaded Atmospheric dirt or dust Wrong grade of brush material
Chattering or noisy brushes	Commutator surface in bad condition Brushes loose in holder Commutator or commutator bars loose Commutator not mechanically true
Brushes overheat	Motor overloaded Brush position wrong Brush tension wrong Poor connection at shunt terminal Wrong grade brush material
Commutator black or discolored	Bad atmospheric conditions Excessive dust or dirt present Wrong grade brush material Brushes spark or overheat (see above)
Commutator overheats	Motor overloaded Brushes spark or overheat (see above) Brush position incorrect Brush tension incorrect Brush material incorrect

CHAPTER 11 Insulating Materials

The life of any motor depends upon the life of the insulating materials used in its construction. Bearings and brushes can be watched and given periodic attention, but when the insulation fails, a complete shutdown usually results and the motor has to be sent to the shop for overhaul. Insulating materials have a twofold job. They must first have the proper characteristics to insulate electrically the windings, and, secondly, they must withstand the heat produced by the passage of the current in the windings. Not only must they withstand this heat but they must also dissipate this heat by transferring it to the air or the surrounding materials. Unfortunately, all good electrical insulating materials now in use are also good insulators of heat. This makes the problem of the selection of the proper insulating material a very real one. While it is fundamentally a design problem, it is nevertheless important for all to know the types of motor insulation likely to be encountered and their limitations.

There are five general classes of insulation set up by the American Standards Association which have become universally accepted by motor manufacturers. Catalogs and bulletins issued by nearly all of the motor manufacturers show the *class* of insulation used in each type of motor listed. When second-hand or rebuilt motors are purchased, the dealer should be required to state the class of insulation used. The standard specifications and their classification follow.

Classes of Insulating Materials

Class O Insulation Class O insulation consists of cotton, silk, paper and similar organic materials when neither impregnated nor immersed in a liquid dielectric.

Class A Insulation Class A insulation consists of: (1) cotton, silk, paper and similar organic materials when either impregnated or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors.

Class B Insulation Class B insulation consists of mica, asbestos, fiberglass and similiar inorganic materials in built-up form with organic binding substances. A small proportion of Class A materials may be used for structural purposes only.

Class C Insulation Class C insulation consists entirely of mica, porcelain, glass, quartz and similar inorganic materials.

Class H Insulation Class H insulation consists of: (1) Mica, asbestos, fiberglass and similar inorganic materials in built-up form with binding substances composed of silicone compounds or materials of equivalent properties; (2) Silicone compounds in rubbery or resinous forms, or materials with equivalent properties. A minute proportion of Class A materials may be had only where essential for structural purposes during manufacture.

Note An insulation is considered *impregnated* when a suitable substance replaces the air between its fibers, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substances in order to be considered suitable, must have good insulating properties; must entirely cover the fibers and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through other cause; must not flow during the operation of the machine at full working load or at the temperature limit specified; and must not unduly deteriorate under prolonged action of heat.

Since all insulating materials eventually break down under heat, limiting temperatures (called hottest-spot temperatures) have been established for most insulation classifications. These are

Class O	90 degrees C
Class A	105 degrees C
Class B	125 degrees C
Class C	Not yet established
Class H	Not yet established

It should be noted that these are maximum temperatures and that practical operating temperatures should be considerably less.

The characteristics of the various insulating materials themselves deserve brief mention. It is interesting to note that the materials alone seldom have desirable characteristics but when used in combination with various varnishes and similar compounds, they become valuable insulating materials.

Asbestos is actually a very poor electrical insulator, but because of its ability to withstand heat, it is an excellent vehicle for insulating compounds. It is one of the few fabrics that termites will not destroy. Asbestos is generally used in the form of spun cloth containing a small percentage of cotton or in the form of paper, where it may contain a small proportion of wood pulp.

Mica is probably the most valuable insulating material in common use. It is an inorganic substance mined in the form of large crystals. These are readily split into thin sheets or flakes. Mica has high dielectric strength, high insulation resistance, and comparatively good heat conductivity. It does not readily absorb moisture and does not deteriorate under conditions of severe heating. The mica splittings, being rather small, are usually built up into larger sheets by a pasting process. Such mica is known commercially as pasted or built-up mica. This is the mica used in the insulation of commutator segments and certain types of coil insulation.

Cotton fabrics are among the oldest insulating materials for motors. Cotton in itself is not suited for high temperature application and absorbs moisture readily. However, when cotton materials are used as a base for various insulating varnishes and compounds, it has remarkably good insulating properties. It is the basic material of Class A insulation and as such is probably the most widely used of all insulating materials.

Fiberglass which is woven from fine threads of glass is finding more and more acceptance as an insulating material. It is less bulky than either cotton or asbestos, is an excellent base for insulating varnishes, and performs very well at high temperatures. It is a Class B insulating material. When used as a base for the new silicone insulating compounds, it forms an outstanding motor insulating material. The use of fiberglass materials without being treated with insulating compounds is not recommended.

Paper of various types is widely used in motor insulation. It may be treated or untreated, depending upon its specific application. Untreated papers tend to absorb moisture and for this reason are less desirable than treated paper. Untreated paper is frequently used in connection with building up windings which are to be treated with varnish and baked upon completion. Insulating papers are available in a wide range of thickness, and for this reason are most useful for armature slot and coil layer insulation.

Vulcanized, or hard, fiber is a dense tough substance which makes a very good insulator. It has high mechanical strength and can be machined with ease. It is often used to support brush holders in motors. Thin sheets of fiber find some use in motor windings but they have the great disadvantage of being susceptible to moisture. The absorption of moisture greatly reduces the insulating properties of fiber sheets and tends to cause them to warp and swell.

Friction tape is a cotton fabric treated with a bitumen compound. It is used very little as an insulating material except on coil end connections. It deteriorates very rapidly with age and for this reason should be coated with a suitable insulating varnish after being applied.

The compounds used to treat insulating materials are generally known as insulating varnishes. These compounds are made from various gums or resins, either natural or synthetic, with drying oils and a suitable volatile solvent. Each manufacturer offers a wide range of types of insulating varnishes, each of which is compounded for a specific purpose. There is no single universal insulating varnish.

Varnishes are generally classified as either air-drying or baking. They are further subdivided into hard and flexible varnish, which in turn may be either clear or black. An air-drying varnish will dry in a few hours at ordinary room temperature. A baking varnish requires from 10 to 16 hours in a properly ventilated oven, the time depending on the varnish itself, the size of the object being baked, and the temperature of the oven.

Silicone compounds are a synthetic product of complex chemical composition. They are commercially available in three major forms; (1) silicone resins, (2) silicone fluids, and (3) silastic, a rubberlike compound. The silicone resins are used to make insulating varnishes, paints, and bonding agents. Silicone fluids find use as waterproofing agents and insulating compounds. Silastic is a trade name for a rubberlike insulating material. Because of their ability to withstand comparatively high temperatures, they have been given a special classification of their own, Class H. It is anticipated that these compounds will come into widespread use when their properties and limitations become better known.

For routine maintenance and repair work, a good grade of air-drying varnish will suffice, but when a motor is given a complete overhaul, the windings should be dipped in an impregnating compound and oven baked. Dipping is a simple, easy method of applying insulating varnish provided the proper equipment is at hand. The varnish is placed in a tank which is usually only slightly larger than the apparatus to be dipped. The varnish should be warmed so that it will more easily penetrate the spaces between the windings. The article should remain under the varnish until the air bubbles cease and is then lifted and held above the tank to permit the excess varnish to drain. After draining, the article is placed in an oven and baked. In dipping a motor armature, the commutator end is kept uppermost. The armature is dipped just deep enough so that the windings are submerged but the commutator remains above the surface.

Because of the tremendous number of brands and grades of insulating varnish on the market, it is impossible to make any specific recommendations. It is suggested that the motor manufacturer be consulted when such compounds are required. It is further suggested that a brand which is readily obtainable locally be used so that, when needed, fresh varnish can be obtained on short notice.

For insulation to effectively serve its purpose, it must be kept clean and dry. Dirty insulation deteriorates rapidly because the surface dirt interferes with the ventilation of the motor and the dissipation of heat from its windings. Moisture reduces the electrical insulation and may cause some of the insulating material to break down completely. A clean, dry motor is essential for efficient operation and long life.

A dry motor which has become coated with dust or grime may be wiped clean with a dry cloth free from lint. Waste material is not suitable because small particles are left behind; these particles may later absorb moisture and collect dust. Wiping is only effective on small equipment where the dust is on surfaces which can be readily reached.

When dirt has collected within the motor, it can be blown out with compressed air. The air should be free from moisture and the pressure should not exceed 45 or 50 pounds per square inch. Excessive air pressure may loosen the windings and have a sandblast effect on the insulation. This is particularly true when the dirt contains gritty material or metal filings. Such material may be removed by suction. Special vacuum cleaners are available for this purpose. However, there is some difference of opinion as to just how effective vacuum cleaning is. Most maintenance men prefer compressed air carefully applied. The blowing out of a motor should be performed in a place where the dirt will not be carried into other equipment by the air stream.

Windings which have become coated with a mixture of dirt and oil can be cleaned by washing with a suitable solvent. Carbon tetrachloride is commonly used for this purpose. The vapors of carbon tetrachloride, while not explosive, are highly toxic and this solvent should only be used in a well ventilated place and workmen should be cautioned against inhaling the fumes. Excessive use of carbon tetrachloride may soften the insulation, particularly if the varnish is of the asphalt type. For such varnishes Stoddard solvent should be used. While commercial Stoddard solvent usually has a flash point of about 100 F, great care should be used, nevertheless, to prevent fires and explosions.

Solvents are generally applied to the windings with a wiping cloth. Sometimes they are used as a spray with compressed air or in a direct stream to flush out the windings. Solvents should not be allowed to remain in contact with insulating materials any longer than absolutely necessary to cleanse them. It should be kept in mind at all times that solvents are hazardrous and proper precautions, including adequate ventilation, should always be taken.

When motors become damp or wet, they must be properly dried. Dampness lowers the value of the insulation resistance and not only interferes with its efficient operation but may also cause a complete breakdown. As a rule, a motor in continuous service will stay at a temperature sufficiently high to prevent condensation of moisture on its windings. An idle motor accumulates moisture rapidly. Motors located in damp places and those which are only used occasionally are frequently provided with electric heaters to maintain a temperature sufficiently above room temperature to prevent condensation of moisture. A motor which has been completely submerged must be cleaned and thoroughly dried before it can be returned to service.

Motors can be effectively dried by the use of a hot-air blower. A well-vented canvas cover is placed over the motor and the hot-air stream directed under the canvas. The air may be heated by steam coils or an electric heater in combination with a fan or blower. Ventilation must be provided to permit the air to circulate through the motor and carry the moisture away. The moisture should not be allowed to boil within the insulation. Drying by this method is a slow process and should be carried on around the clock for 24 to 48 hours. The motor should be checked from time to time during the process to see that it does not become too hot and that the air is circulating properly.

Drying can also be accomplished by directing the rays of infrared heat lamps on the windings. Racks can be easily built for mounting the heat lamps and arranged to direct the rays so that the windings are completely bathed in radiant heat. Here too, the temperature must be carefully watched to prevent it from becoming excessive. It should be remembered that circulating air is always necessary to carry away the moisture extracted.

When a motor has been submerged in salt water, the problem of drying is considerably more difficult. Salt may be deposited within the windings and cause trouble at a later date if not completely removed. Such a motor must be dismantled and flushed out with plenty of fresh water until all traces of salt disappear. This may take considerable time as it is absolutely essential to wash all the salt out of the winding. In addition to the salt, there is usually a certain amount of mud and silt deposited on the windings of a motor which has been submerged. All this must be washed out of the windings. After the motor has been flushed clean, the windings are then dried and the motor reassembled. If the motor has been submerged in salt water for some time, complete rewinding is recommended.

The commutator of a motor which has been submerged is likely to have moisture in the segment insulation. This is very difficult to remove without loosening the commutator segments. It is often more economical to install a new commutator, especially if the old one has had considerable wear. It goes without saying that the brush holders, all copper parts, contact surfaces and connections should be thoroughly cleaned and polished before a submerged motor is returned to service.

CHAPTER 12 The Series Motor

THE series motor derives its name from the fact that the armature and field circuits are connected in series. The schematic representation of the series motor is shown in Fig. 42. Since the field and the armature are connected in series, all the current which flows through the armature must also flow through the field. For this reason, the field coils on a series motor consist of but a comparatively few turns of fairly large wire.

It should be remembered that the field strength or magnetic flux is the product of the field current in amperes by the number of turns in the coil on the field pole. Thus, when considerable current passes through the field coil, only a few turns of wire are necessary to produce the required flux. Increasing the current increases the flux until the iron in the magnetic circuit reaches a saturation point. Beyond the saturation point of the iron, a further increase in the current has but little effect on the resultant flux. This can be visualized by examining a typical magnetization curve such as the one shown in Fig. 43. Here it may be seen that as the exciting current is increased, the magnetic flux increases in almost direct proportion until a point is reached where

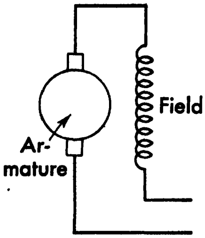


FIG. 42 Schematic representation of the series motor.

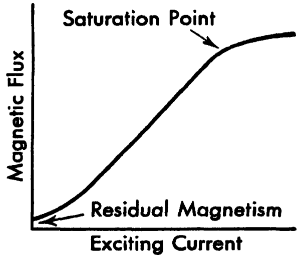


FIG. 43 Typical magnetization curve.

a further increase of the exciting current produces a smaller increase in the magnetic flux. The point where the curve begins to bend is the *saturation point.* This point varies with the composition of the magnetic material as well as the mass of that material. For a given mass every magnetic material has a very definite saturation point. This fact must always be kept in mind when studying the characteristics of an electric motor.

In Chap. I, a brief discussion of the subject of torque was given. The fundamental expression for torque was given in equation (2) as

$$T = KI\phi$$

Keeping in mind that in the series motor, all the current passes through both the armature and field circuits, suppose the current is doubled. Then in the basic expression for torque, the armature current (I) is doubled. In addition to the armature current being doubled, the current flowing in the field coils is also doubled. Since the flux ϕ is the product of current by the number of turns, the field flux is doubled when the line current is doubled. Thus, in the equation for torque, not one, but two, factors are doubled when the line current is doubled. This is true only where the iron in the motor is below the magnetic saturation point. After the saturation point of the iron is reached, doubling the current in the motor has only a slight effect on the available flux. Since the flux is directly proportional to the current (below saturation), the equation for torque in the series motor may be written as

$$T = KI^2 \qquad \text{(approximately)}$$

The factor I^2 represents armature current times field current. Thus the doubling of the current in a series motor increases the torque four times. In practice, magnetic saturation and armature reaction tend to prevent the torque from increasing as rapidly as the square of the current. However, the series motor has the characteristic of being able to develop a comparatively large increase in torque with a moderate increase in current.

When any motor is started, the initial current flow may be as much as double the rated load current. In the series motor, this increased initial current greatly increases its starting torque. This makes the series motor particularly useful in applications requiring frequent starting under heavy load. This is a very desirable characteristic, and the series motor would have many applications if it were not for the fact that it also has some characteristics which are considered very undesirable in a great many industrial applications. One of these undesirable characteristics is its speed behavior under load.

It will be recalled that the fundamental speed expression was given in equation (4) as

$$S = K\frac{V - I_aR_a}{\phi}$$

Since the current flowing in the armature and the field are identical in the series motor, the factor I_a may be written simply as the motor current I. However, this current passes through two resistances, that of the field and that of the armature. Therefore, in place of R_a the expression $R_a + R_f$ is used. Making these changes in our original equation, the speed of the series motor now becomes

$$S = K\frac{V - I(R_a + R_f)}{\phi} \tag{5}$$

That part of the expression given as $I\ (R_a + R_f)$ represents the voltage drop due to the current flowing through the combined armature and field circuits. It is commonly referred to as the IR drop.

As the load on a series motor increases, the current also increases. The current increase makes the voltage drop, that is, $I(R_a + R_f)$, larger. As a result the numerical value of the expression $V - I(R_a + R_f)$ is smaller. It will be recalled from equation (3) that this represents the expression of the counter electromotive force in the motor. It should be noted that the flux ϕ also increases with the current. The combination of the decrease in counter electromotive force and the increase in flux reduces the value of the speed S. All this simply means that when the load increases, the increase in current causes the series motor to slow down. Conversely, the series motor will increase its speed as the load is reduced because the flux ϕ decreases and the armature must speed up in order to develop the required counter electromotive force. As the load is further removed the speed continues to increase, and if the load is removed altogether the speed will become dangerously high and the motor will race to destruction. A series motor should therefore never be used in any application where it is possible for it to operate without load or with a belt drive as failure of the belt would remove the load.

Since the speed of the series motor varies with every change in load, it is not suited for applications where the load is variable or a constant speed drive is required. This disadvantage tends to offset the unusually good torque characteristics of this type motor.

Notwithstanding these facts, the series motor is ideal for certain uses. It is particularly suited for driving streetcars and locomotives. It also finds application in certain types of cranes and hoists. In these applications, the load can not be completely removed and the torque characteristics enable it to accelerate the streetcar or hoist very rapidly under heavy load.

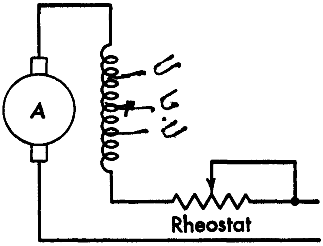


FIG. 44 Rheostat connections in a series motor starting circuit.

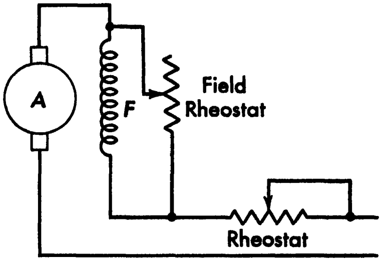


FIG. 45 Series motor connections for speed increase.

When a series motor is started, some means must be used to limit the initial rush of current from the line until the motor attains proper speed. At zero speed, there is no counter electromotive force, and since the ohmic resistance of the motor is low, there would be an enormous inrush of current the instant the standing motor was connected to the power supply. It is therefore customary to use a variable resistance (a rheostat) in series with the motor. Figure 44 shows a commonly used arrangement to accomplish this. A feature of this arrangement is that the resistance is always in series with the motor. Instead of gradually removing the resistance as the motor comes up to speed, it is gradually "shorted-out." In this way, should the movable arm of the rheostat fail to make proper contact as it passes from point to point, all the resistance is immediately in series with the motor. This scheme is essential to safe operation. The rheostat can be used as a means of speed control, provided that it is heavy enough to continually carry the required current without undue heating. When the series resistance is entirely removed from the circuit, that is, completely shorted-out, the motor operates at normal rated speed for the given load. To make a series motor run faster than normal for a given load, an arrangement as shown in Fig. 45 may be used. Here a second variable resistance is shunted across the field winding only. Its purpose is to reduce the field strength, which in turn causes the motor to speed up. By using the two variable resistances in combination, any speed from zero to above normal may be obtained.

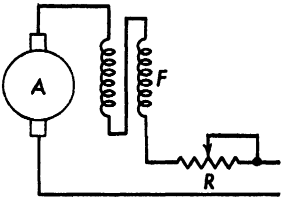


FIG. 46 Series motor with two-section field connected in series.

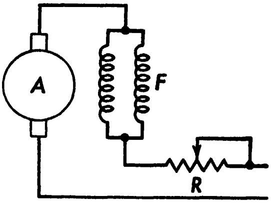


FIG. 47 Series motor with two-section field connected in parallel.

In another form of speed control, the series field circuit of the motor is split into two parts. In starting the motor, a controller is used which first connects the two fields in series. In addition, the starting resistance is also connected in series with the motor, so that the current is required to first pass through the starting resistance, then the first field section, and finally the second field section. Movement of the controller lever cuts out the starting resistance in easy steps while the two field sections remain in series. When the starting resistance has all been removed from the circuit, the next step of the controller connects the two field sections in parallel and at the same instant reinserts the entire starting resistance. As the movement of the controller continues, the starting resistance is again removed step by step until finally the two field windings are in parallel with no resistance in series. Reference to Figs. 46 and 47 will make this clear. In Fig. 46 the field of the motor is divided into two sections which are connected in series, whereas in Fig. 47 the two sections of the field winding are connected in parallel. The variable resistance used for starting is in series with the motor at all times.

A somewhat similar arrangement is used in streetcar service where two separate series motors are used. Here the two motors are first operated in series with each other as the resistance is removed step by step, until the half-speed position of the controller is reached. In this position, the two motors are connected directly across the line in series with each other without any external resistance. As the controller is advanced from half speed to full speed, the two motors are connected in parallel and the starting resistance reinserted in the circuit. This resistance is again removed step by step until, in the final full-speed position, each motor is connected directly across the line with all external resistance removed. In most applications the use of a series resistance to control speed is not economical because considerable energy (in the form of heat) is wasted. However, it should be noted in connection with the streetcar control, that at both half speed and full speed, there is no external resistance in the circuit.

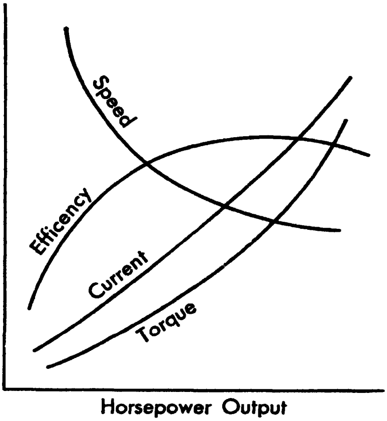


FIG. 48 Characteristic curves of the series motor.

Small series motors are often used on alternating current circuits. Such motors are called *universal* motors because they operate on either direct current or alternating current. Since the field and the armature are in series, the relationship between the field and the armature is the same at any given instant as the alternating current reverses its direction. The use of series motors on alternating current circuits is limited to the small sizes (mostly household appliances) because of the various increased losses introduced by certain characteristics of alternating current.

To better visualize the characteristics of the series motor, a set of curves known as *performance curves* may be drawn. Figure 48 shows a typical set of series-motor performance curves. The curve representing speed sweeps in a downward direction as the load in horsepower increases while the torque curve sweeps upwards. The efficiency increases until rated load is reached and then drops off. The current consumption expressed in amperes is more or less parallel to the torque curve. Similiar performance curves will be given for other types of motors and it will be interesting to compare them.

In many series motors, only two leads are brought out to the terminal box for the purpose of making connections. However, it is rapidly becoming standard practice to bring all the individual leads from the internal windings to a connection box which is usually located on one side of the motor frame. This is necessary for testing the windings and to facilitate connecting the control mechanism. The terminals thus brought out are identified by a system of marking which has become more or less standardized with all manufacturers. The symbols commonly used for this purpose are:

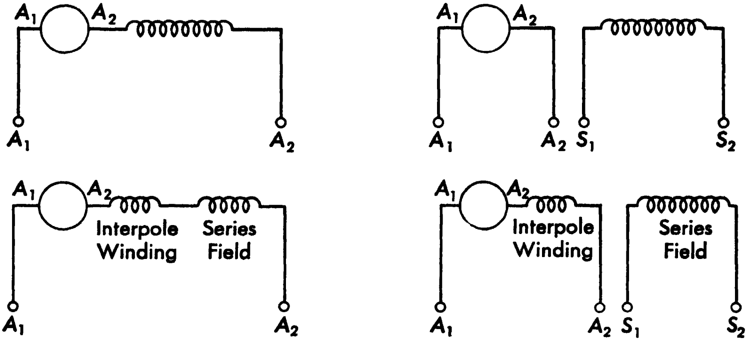


FIG. 49 Standard notation and terminal arrangements for the series motor.

Armature	*A1*, *A2*
Series Field	*S1*, *S2*, *S3*, etc.
Interpole Winding	*H1*, *H2*, *H3*, etc.

The diagrams shown in Fig. 49 show some of the more common arrangements of the internal windings used on the series motor.

On some special-application series motors where the field winding is split into two parts, the leads from each part are brought out to separate terminals. In such instances the terminals of one section are marked *S1* and *S2*, while those of the other section are designated by *S3* and *S4*. Opposite terminals of the same winding are generally designated by consecutive numbers; thus *S1* = *S2* are the terminals of one winding, while *S3* = *S4* are the terminals of the other winding.

CHAPTER 13 The Shunt Motor

THE shunt motor derives its name from the fact that the field circuit is in parallel with the armature circuit. That is to say, the field winding is *shunted* across the armature. The schematic representation of the shunt wound motor is shown in Fig. 50.

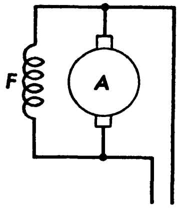


FIG. 50 Schematic representation of the shunt motor.

Since the field winding is connected directly across the supply line, it consists of a comparatively large number of turns of relatively small wire. This is necessary to keep the field current within safe limits. The actual current in the field circuit is generally less than 5 per cent of the total motor current. Because of the comparatively low value of this current, the field circuit may be connected directly across the supply line without damage. It should also be pointed out that since the field coils are connected directly across a constant voltage supply line, a constant current flows, which in turn sets up a nearly constant magnetic flux within the motor. The fact that the field strength is constant is one of the basic characteristics of the shunt wound motor.

It has already been shown that the torque of a motor is directly proportional to the armature current and the field strength. Since the field strength is practically constant in the shunt motor, its torque will vary almost directly with the armature current. In the case of the series wound motor, it was shown that the torque was proportional to the square of the current. The starting torque of the shunt motor is therefore not as large as that of the series motor, yet because of the magnitude of the initial inrush current, it is sufficiently large for the vast majority of industrial applications.

When the load on a shunt motor is increased, the motor tends to slow down slightly. Since the field strength is constant, a slight slowing down of the armature reduces the amount of counter electromotive force developed. The reduction in counter electromotive force permits more current to flow in the armature circuit. This increased current flow enables the armature to develop sufficient torque to meet the demand of the increased load.

Although it is necessary for the shunt motor to slow down in order to permit the current in the armature circuit to increase sufficiently to develop the required torque, actually the reduction in speed is so slight that, for all practical purposes, the shunt wound motor is considered a constant speed motor. A review of the fundamental expression for speed, equation (4), will show that in the case of the shunt motor, all the factors in the equation are constant except the armature current I_a. An increase in the armature current I_a will reduce the value of the $(V - R_aI_a)$ portion of the speed equation. However, the value of the term R_aI_a is comparatively small as compared with the value of V, so that the resultant change in the value of the whole expression $(V - R_aI_a)$ is small. In commercial motors, this change in value is ordinarily less than 5 per cent. The speed variation due to this change in armature current is therefore small and the shunt motor is considered a constant speed motor.

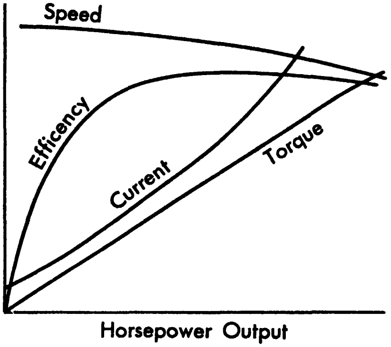


FIG. 51 Characteristic curves of the shunt motor.

There is another factor, however, which must be taken into consideration. While the flux emanating from the field poles of the shunt motor is constant, there is a slight change in the actual available flux due to the effects of armature reaction. An increase in the armature current causes an increase in the strength of the magnetic field set up by the armature inductors. This increased flux opposes and tends to cancel out a small portion of the original field flux. This reduces the value of the effective field flux of the shunt motor. The decrease in this flux, when applied to the speed equation, has the effect of offsetting some of the slight loss in value of the $(V - R_aI_a)$ portion of the equation. This helps the shunt motor to maintain constant speed. Despite these factors, there is still a slight loss of speed with an increase of load.

The characteristic curves of the shunt motor are shown in Fig. 51. It should be noted that the speed curve drops slightly as the load increases and that the value of the torque is practically a straight line, indicating that it is directly proportional to the horsepower output of the motor. Because of these two characteristics, the shunt motor is more widely used in industry than any other type motor.

Variation in speed of a motor due to changes in load is generally expressed as a percentage called *per cent of speed regulation.* This may be defined as

$$\text{Per cent speed regulation} = \frac{\text{no-load speed} - \text{full-load speed}}{\text{full-load speed}} \times 100$$

When this percentage is small, the motor is said to have good speed regulation. A typical shunt motor may be taken as a numerical example. Suppose the no-load speed is 1800 rpm and the full load speed 1725 rpm. Then the speed regulation is

$$\frac{1800 - 1725}{1725} \times 100 = 4.3 \text{ per cent}$$

This value is typical of the speed regulation of a standard commercial shunt motor.

A stabilized shunt-wound motor is a shunt motor having a light series winding added to the field poles, to prevent a rise in speed or to obtain a slight reduction in speed with the increase in load. This winding is entirely separate from the normal shunt-field winding and is connected in series with the armature. Although this type of motor has two field windings, the series field winding is so light that the motor is not classified as *compound wound.* The net effect of the added series field is to modify the speed characteristics and at the same time improve the torque of the motor. The light series winding is so connected that upon an increase in load, the increased armature current increases the available field flux as it passes through the series field winding. The stabilized shunt-wound motor is particularly adapted for applications where the load changes rapidly. Under such conditions, the standard shunt motor may tend to have unstable speed characteristics. The additional light series field winding overcomes this, hence the term *stabilized* is applied.

When starting a shunt motor, means must be provided to prevent the initial inrush of current through the low-resistance armature winding. It is not necessary to limit the initial current flow in the field winding as it has already been shown that this circuit has sufficient resistance to enable it to be connected directly across the line. There fore, the arrangement suggested for starting the series-wound motor is not suited for use with the shunt motor. Figure 52 shows one common method of starting the shunt motor. After closing the line switch shown in this figure, the arm is moved up to the first point. In this position, all the starting resistance is in the armature circuit and the field circuit is connected directly across the supply line. As the lever arm is moved up over the contact points, the amount of the resistance in the armature circuit is gradually reduced while the field circuit continues to be connected directly across the supply line. This is a basic starting arrangement. The circuits of starting devices vary with each maker. Some of the more common starting circuits will be discussed in Chap. 19 on starting the direct current motor.

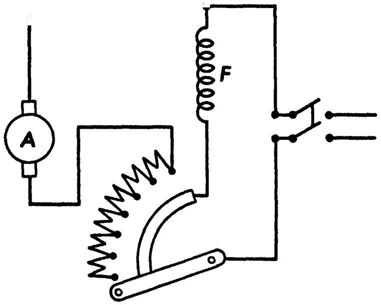


FIG. 52 Typical starter connections for a shunt motor.

While the shunt motor is basically a nearly constant-speed motor, its operating speed can be controlled in a number of ways. Speed increase over normal can be achieved by weakening the magnetic field strength In the previous chapter on the series motor, it was explained how reduction of the field strength brings about an increase in the motor speed. This also applies to the shunt-wound motor. To accomplish the change in field strength, a rheostat which is separate and independent of the starting control is inserted in the field circuit. This rheostat enables the value of the field current to be controlled without affecting the armature current. By this means the speed of the commercial shunt motor can be increased up to about 25 per cent above normal rated speed. If even greater speeds are required, it is generally more efficient to use a specially designed adjustable speed motor.

It should be noted that the term *adjustable* speed motor applies to a machine whose speed can be adjusted as and when desired, and when once set at the selected speed, remains practically unaffected by changes in load. The term *varying* speed motor applies to a machine whose speed varies with changes in load.

The speed of a shunt motor can be decreased by using a resistance in series with the armature circuit. Such a resistance must be heavy enough to continously carry the full load current of the armature circuit. The starter shown in Fig. 52 could be used for this purpose, provided it could handle the armature current without overheating. Often a separate rheostat connected in series with the armature circuit is used for this purpose. This method is not very efficient because the current causes the resistance to heat up, and energy is thereby wasted. Another disadvantage of this method is that the addition of resistance in the armature circuit gives the motor poorer speed regulation. It is an exceedingly useful method however, where occasional, rather than regular, reduction of speed is required.

By using a combination of field control and armature control it is possible to obtain a wide range of speed from 0 to about 25 per cent above normal speed. Notwithstanding these arrangements, the shunt motor is basically considered to be an almost constant speed motor.

Leads from all windings are usually brought out at a connection box on the motor frame to facilitate testing and connecting the control mechanism. These terminals are usually identified as follows:

Armature	*A1*, *A2*
Shunt Field	*F1*, *F2*
Interpoles	*H1*, *H2*

As a rule, the terminals from the interpole windings are not brought out to the connection box.

When the leads of a shunt motor are unidentified, it becomes necessary to determine which are the terminals of the field winding and which are those of the armature winding before the motor can be properly connected. Often the field leads can be distinguished by inspection as a smaller size wire is frequently used for this circuit as compared to the size of the wire used for the armature leads. When all wires are the same size, they can usually be identified by a simple test. Two flexible leads are run from the supply line with an ordinary lamp in series with one of these leads, as shown in Fig. 53. One lead is touched to motor terminal No. 1 and the other lead to terminal No. 2. If the lamp fails to light, one of these terminals may be assumed to be that of the armature circuit and the other of the field circuit. Different combinations are then tried until the test lamp lights. A bright light indicates the armature leads, for the internal resistance of the armature circuit is low. A dim light indicates the field terminals, because of the higher resistance of this circuit. Once the terminals have been identified, they should be marked for future reference.

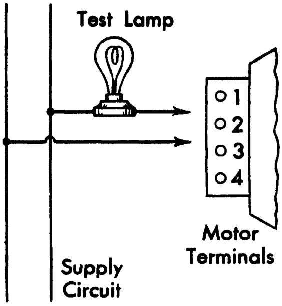


FIG. 53 Test for identification of motor terminals.

The arrangement of the internal connections and the standard identification of terminals in various types of shunt-wound motors are shown in Fig. 54.

Where a stabilizing winding is used, it is connected in series with the armature circuit between terminals *A1* and *A2* just as the interpole winding is connected.

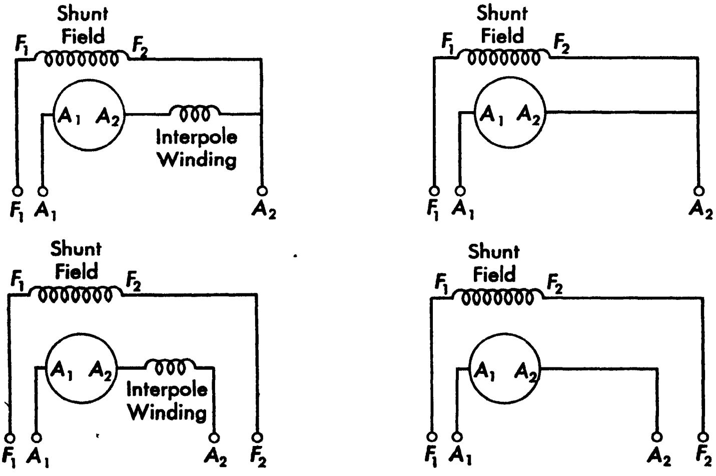


FIG. 54 Standard notation and terminal arrangements for the shunt motor.

CHAPTER 14 The Compound Motor

A COMPOUND-WOUND motor has two separate field windings on each of its field poles. One winding is connected in series with the armature circuit and the other is connected in parallel. Thus it is actually a combination of the series and shunt motors. When the two field windings are so connected that they aid each other in the production of the field flux, the motor is known as *cumulative* compound. When the two field windings oppose each other, the motor is said to be a *differential* compound motor. The cumulative-compound motor is the more common of the two types.

The operating characteristics of the compound motor lie between those of the series and shunt motors. By properly proportioning the two field windings, the characteristics of the compound-wound motor can be made to approach either those of the series motor or those of the shunt motor. Figure 55 shows the conventional schematic representation of the compound-wound motor.

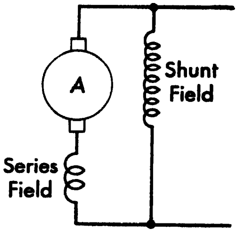


FIG. 55 Schematic representation of the compound motor.

In the cumulative-compound-wound motor, the field flux increases with the load due to the increase of current flowing in the series winding. This causes the speed of the motor to drop off more rapidly than does that of the shunt motor. At no load, very little current flows in the series field and the motor behaves as a shunt motor. It therefore has a definite no-load speed and does not race in the manner of a series motor.

Since the flux increases with an increase in load, the torque increases in a greater proportion than does the armature current. This characteristic is borrowed from the series motor. Therefore the cumulative compound motor requires less current than the shunt motor requires for a given increase in torque. This characteristic of the compound motor makes it ideal for such applications where a large starting torque is required and a variation in speed is not objectionable. Some of these applications are the driving of large punch presses, heavy jaw crushers, steel rolling mills, and the like. In most of these applications heavy loads are suddenly applied.

The speed variation of the commercial cumulative compound motor may be as much as 25 per cent, whereas with the shunt motor, this speed variation is usually less than 10 per cent. When a heavy load is suddenly applied, the speed variation of the compound motor causes it to act somewhat like a flywheel. The stored energy helps to carry it over the load peak.

In applications requiring a large starting torque but a reasonably constant running speed, the compound motor can be so arranged that the controller removes the series winding when the motor reaches rated speed. The starting characteristics of such a compound motor approach those of the series motor, while the running characteristics are those of the shunt motor. This arrangement is ideal where the load is fairly constant once the rated speed is reached.

In the differential-compound motor, the field flux decreases with an increase in load due to the opposing action of the series field winding. Thus the speed of the motor does not drop off with an increase in load as much as a shunt motor does. By properly proportioning the two field windings, a differential compound motor can be made to operate at the same speed at both no load and full load. There will be a slight variation in the speed between these two points however. It is even possible to design such a motor so as to cause an increase in speed with an increase in load.

Since the field flux is reduced with an increase in the armature current, the torque increases in smaller proportion and, therefore, such a motor requires more current for an increase in torque than does the shunt wound motor.

The speed-current curve of the differential-compound motor stays more nearly horizontal than for most other types of motors. However, this motor has one objectionable characteristic which makes it undesirable for most commercial applications. As increased loads are placed on the differential compound motor, it draws more armature current. As the armature current increases, a point may be reached where the magnetic flux produced by the series field winding completely neutralizes the flux produced by the shunt field. At this point the motor becomes unstable. It will not race or run away because of the load on it, but a heavy current will flow through the armature circuit. This heavy overload current will cause the series field to predominate over the shunt field and thus cause a reversal of the motor's rotation. Because of this unstable speed characteristic, the differential compound motor is not extensively used. Where the differential-compound motor is used, protective devices must be installed in the motor-control circuit to prevent this.

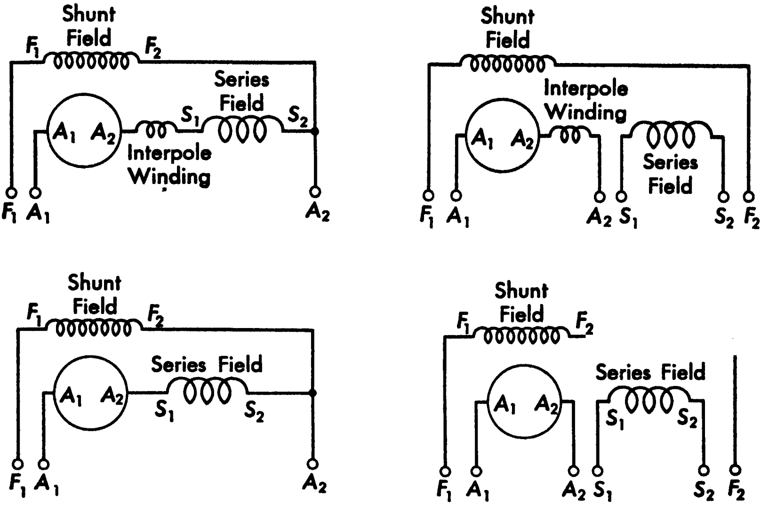


FIG. 56 Standard notation and terminal arrangements of the compound motor.

As with other types of motors, the terminals of all the windings of the compound motor are brought out at a connection box and are identified by the standard terminal code marks. These are:

Armature	*A1, A2*
Shunt Field	*F1, F2*
Series Field	*S1, S2*
Interpoles	*H1, H2*

In connecting a compound motor where the field windings are all brought out separately to the terminal box, care must be taken to properly connect the sequence of the windings so that they will aid each other in the case of the cumulative-compound motor, or oppose each other if the machine is a differential compound motor. The order in which the terminals are numbered usually (but not always) gives an indication of the direction of the winding. In case of doubt, they may be tested by applying the current to each winding separately and checking the polarity of the resulting field with a pocket compass. In making such a test, it should be remembered that the series-field winding has a very low resistance and should not be connected directly across the supply line without a protective resistance in the circuit.

A compound motor may be started in the same way as the shunt motor. The connection diagram given for starting the shunt motor can therefore be used for starting the compound motor.

The arrangement of the internal connections of the compound-wound motor is shown in Fig. 56.

CHAPTER 15 Selection and Application

THE selection of the ideal direct current motor to do the particular job at hand efficiently and economically is not always a simple matter. Many varied factors must be considered and carefully weighed, one against the other. The final selection will usually be a compromise between electrical characteristics, mechanical construction, and economic considerations.

It would be well to review briefly the fundamental electrical characteristics of the three basic types of direct-current motors from the standpoint of application.

Series-wound motors are inherently varying speed motors. They start with powerful torque and relatively low starting current with the torque increasing at a considerably greater rate than in direct proportion to the increase in current. They are capable of starting and accelerating heavy loads with a lower current consumption than any other type motor. On light or no loads, the speed may become dangerously high, hence such motors can be employed only where the load is never entirely removed or where close supervision is always maintained. A series-wound motor should never be connected by belt to its load, but always by gear, chain, or coupling. Typical applications of series motors are where wide speed changes are permissible and desirable, such as: hoists, cranes, traction, winches, lift bridges, gates, car dumps, baling presses, and coke oven machinery.

Shunt-wound direct-current motors are essentially constant-speed motors. When operated on a constant-voltage supply, they maintain practically constant speed regardless of variations in load. There is, of course, some slight speed variation, as has already been pointed out, but the change from no-load to full-load speed is usually less than 10 per cent. They develop a fairly good starting torque under average conditions. Typical applications of the shunt motor are: fans, blowers, centrifugal pumps, conveyors, woodworking machinery, metalworking machinery, elevators, line shafts, printing presses, and mixers.

Compound motors have both series- and shunt-field windings, and the relative strength of the two fields determines to what extent the motor approaches the shunt or series characteristics. In general, they have a high starting torque approaching that of the series motor with the definite no-load speed characteristics of the shunt motor. Approximate speed drop from no load to full load is about 25 per cent. They are used extensively where the motor must develop high starting torque in order to accelerate the driven machine. Typical applications of the compound wound motor are: plunger pumps, punch presses, shears, bending rolls, geared elevators, conveyors, crushers, bulldozers, and metal-drawing machinery.

The first consideration in the selection of a direct current motor concerns the voltage available. There are three standard direct current voltages in common use. They are: 115 volts, 230 volts, and 550/600 volts. It is to be kept in mind that the lower the voltage, the larger the current for a specified power output. Large current means larger conductors (greater investment in copper) and usually larger electrical losses. Therefore the highest voltage available should be given consideration. On the other hand, the higher voltages increase the hazard to the operating personnel, increase the cost of protecting the wiring, and may increase both the size and cost of the associated control mechanism. In general, motors up to 25 horsepower can be operated on 115 volts, while motors in the range of 25 to 200 horsepower should be operated on 230 volts. Over 200 horsepower the voltage should be 550/600 volts.

Where motors are subject to fluctuating voltages, the compound wound motor is to be preferred, since the tendency to overheat is less than in the shunt wound motor. Most commercial direct current motors will operate successfully at normal rated load at any voltage no more than 10 per cent above or below name plate rating. Table IV indicates some of the general effects of voltage fluctuation for the shunt- and compound-wound motors.

Conditions surrounding the motor determine the type of enclosure. Chapter 2 discusses the standard types of motor enclosures and Table I outlines the conditions under which each type enclosure should be used.

Arrangement of the driven machine usually determines whether a horizontal- or vertical-type motor is best suited. Horizontal motors are generally less expensive. Most ball-bearing motors will operate in either position. Some applications will momentarily tilt the motor; others may completely invert it. Under such conditions, means must be provided for proper lubrication and for prevention of oil leakage. Special bearing construction may also be required to handle the end thrust when motors operate in positions other than horizontal. Ball-bearing motors will take a moderate amount of thrust, but extremely heavy thrusts may require special plate-type oil-lubricated bearings. If the motor is to operate in any unusual position, the manufacturer should be so advised at the time the motor is purchased. Figures 57 and 58 show the cross section of typical horizontal sleeve-bearing and ball-bearing motors.

Precision grinders and similar equipment adversely affected by vibration, require specially balanced armatures to hold vibration to a minimum. Such armatures are dynamically balanced at all running speeds before being installed in the motor. In the case of high-speed blowers, both the fan and the armature should be dynamically bal-

TABLE IV Effects of Voltage Variation

Voltage variation	Torque	Full-load speed	Full-load current	Max. overload capacity
		SHUNT WOUND		
120% Voltage	Increase 30%	110%	Decrease 17%	Increase 30%
110% Voltage	Increase 15%	105%	Decrease 8.5%	Increase 15%
90% Voltage	Decrease 16%	95%	Increase 11.5%	Decrease 16%
		COMPOUND WOUND		
120% Voltage	Increase 30%	112%	Decrease 17%	Increase 30%
110% Voltage	Increase 15%	106%	Decrease 8.5%	Increase 15%
90% Voltage	Decrease 16%	94%	Increase 11.5%	Decrease 16%

anced as a unit if excessive vibration is to be avoided. Motor manufacturers will supply dynamically balanced equipment at a slight additional cost. When dynamically balanced armatures are removed from the motor for repairs, they should again be dynamically balanced before being reinstalled.

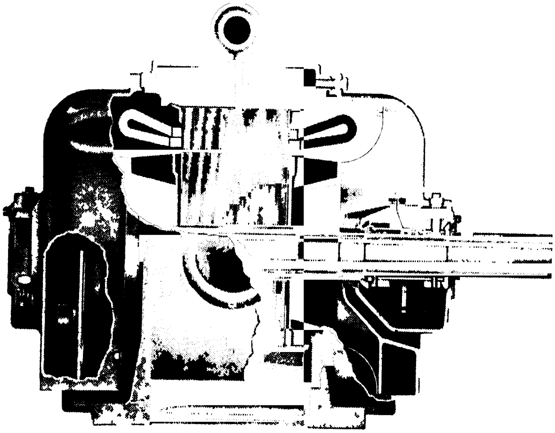


FIG. 57 Cutaway view of a sleeve bearing motor. (*Westinghouse Electric Corp.*)

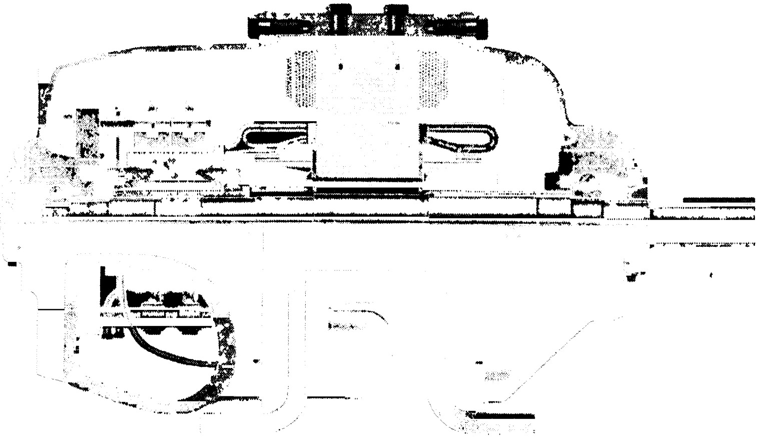


FIG. 58 Cutaway view of a ball bearing motor. (*General Electric Company.*)

The horsepower requirements of a given application determines the size of the motor. If the motor is not of sufficient capacity to handle the normal load, it will heat excessively, have difficulty in accelerating the load and maintaining the rated speed, have poor commutation (indicated by excessive sparking), and a relatively short life. On the other hand, if the motor is unnecessarily large—a condition known as *over motoring*—it is extravagant, wasteful, and inefficient. It is therefore necessary to select a motor with a horsepower rating as close to the actual load requirements as possible. All motors will stand some overloading for short periods, but no motor can be expected to perform properly if continually overloaded.

When the maker of the driven machine specifies its horsepower requirement, the matter is simple. Fortunately, in most cases this information is supplied when the equipment is purchased. Without this information, it is necessary to determine the actual horsepower requirement by test or the estimated horsepower requirement by calculation.

To make a test, a set of instruments known as an *industrial analyzer* is generally used. A tachometer to measure speed is also necessary. If these instruments are not at hand, they can usually be borrowed or rented from a motor supply house. The industrial analyzer is an assembly consisting of a voltmeter and ammeter (sometimes a wattmeter also) mounted in a portable case. An arrangement of terminals and selector switches enables the instrument to be used on a wide range of voltages and current values. A motor judged to be of sufficient size operates the machine. If such a motor is not at hand, one can be rented for the test. With the motor driving the load at the rated speed (determined by the tachometer), readings of the current and voltage are taken under typical operating conditions. The test should be continued until the readings on all meters stabilize. With the volts and amperes known, horsepower can be computed from

$$\text{HP} = \frac{\text{volts} \times \text{amperes} \times \text{efficiency}}{746} \tag{6}$$

To make the numerical computation, it is necessary to assume a value for the efficiency of the motor. Table V gives the approximate values of the efficiency of commercial direct current motors.

Where the load on the machine varies with time and repeats its duty cycle at regular intervals, the size of the motor required can be calculated by the *root-mean-squares* method. The procedure is as follows. Multiply the squares of the horsepower required for each part of the cycle by the time duration of that cycle in seconds. Total the results and divide the sum thus obtained by the total time (in seconds) for the complete duty cycle. The square root of this last result gives the horsepower. A numerical example will make this method clear. Suppose a certain load requires 180 HP for 5 seconds. Then for the next 13 seconds in the cycle the required load drops to 109 HP. Following this, the load drops to 60 HP for 3 seconds, after which the motor is at rest for 25 seconds. The computations for this duty cycle are:

5 sec. at 150 HP = $150^2 \times 5$ or 112,500
13 sec. at 109 HP = $109^2 \times 13$ or 154,453
3 sec. at 60 HP = $60^2 \times 3$ or 10,800
25 sec. at 0 HP = 0
46 sec. (total) 277,755 (total)

now divide $\frac{277{,}753}{46} = 6{,}038$

square root of 6,038 is approx. 77.7 HP required.

TABLE V Motor Efficiencies

Rated HP	PER CENT EFFICIENCY		
	Half load	Three quarters load	Full load
1	70	73	75
2	72	77	78
3	72	77	79
5	77	81	82
7½	79	82	83
10	81	83	85
15	81	84	86
20	82	85	86
25	83	86	87
30	84	87	88
40	85	87	88
50	86	88	89
75	86	89	90
100	86	89	91
150	87	90	91
200	89	91	92

Thus a motor of this rating is sufficient to operate the load for the given duty cycle.

If the driven machine regularly operates at more than one speed, the horsepower required at each speed must be determined in order to select the proper motor. The horsepower-speed relationship for any required constant speed is

$$\text{HP} = \frac{\text{Torque (pound-feet)} \times \text{speed}}{5{,}250} \tag{7}$$

The inertia or flywheel effect of the rotating parts of the driven machine directly influence the accelerating time. Too long an accelerating time may cause overheating both in the motor and its control equipment. The starting torque, often called *breakaway* torque, may vary from 10 per cent to 250 per cent of the normal full load torque. Additional torque is also required after the motor starts in order to bring the driven load up to rated speed. This flywheel effect is known in mechanics as the *moment of inertia.* It is expressed mathematically as WR^2, where W is the weight of the rotating object in pounds and R is the radius of gyration in feet. The computation of WR^2 is a complex problem which is beyond the scope of this book. However, numerical values of WR^2 for common mechanical objects of various types and shapes are to be found in tables given in most engineering handbooks. Nearly all rotating members of the average driven machine are made up of a combination of these basic objects, and the WR^2 for the complete rotating member is the sum of the values of WR^2 of its component parts. With the WR^2 known, the horsepower required to accelerate a machine from zero to full rated speed in a given time can be computed from

$$\text{HP} = \frac{WR^2 \times RPM^2}{1.62 \times 10^6 t} \tag{8}$$

where t is the time in seconds to reach full rated speed.

The frequency of starting affects the size of the motor, particularly if the driven machine has a high WR^2. Machines started frequently require a motor of larger horsepower rating than those which are started only occasionally. Because of the large inrush of current at the moment of starting, constant starting will cause a motor to overheat, unless it is of sufficient size to dissipate the heat caused by such frequent inrushes of current.

In certain special cases, chiefly because of space limitations, two motors of identical rating are used to drive a machine in place of a single larger motor. The two identical motors are operated in parallel. With both motors connected to the same machine, their speeds are identical. Unfortunately the load is not always equally divided between them. This is because it is impossible to manufacture two motors with identical speed-torque characteristics commercially due to slight variations in the mass of the iron in the frame, the magnetic properties of the materials used, bearing friction, etc. These slight variations show up as a difference in torque when the speeds are fixed.

The series-wound motor is better suited for parallel operation than the shunt-wound motor because there is less variation in torque as compared with its speed. In the shunt motor, a large variation in torque corresponds to a comparatively small variation in speed, hence two shunt motors operating in parallel may take unequal parts of the load. This will set up stresses within both the load and the motor and will result in generally unsatisfactory operation. In some instances, this can be compensated for by use of especially designed controls, but since this complicates the installation, it is not frequently resorted to.

Consideration must also be given to the speed requirements of the driven load. If constant speed is essential to the application, a constant speed motor with good speed regulation should be selected. When more than one speed or range of speeds are required, an adjustable speed motor should be chosen. Standard commercial direct current motors are generally available with rated speeds as indicated in Table VI.

TABLE **VI** Standard Motor Speeds

Number of poles	Theoretical no-load speed rpm	Rated full-load speed rpm
2	3600	3500
4	1800	1750
6	1200	1175
8	900	850
10	720	690
12	600	575

Should the driven machine require a different speed, it may be obtained by suitable gearing or belting. *Gearmotors* have been especially developed for this purpose. These motors combine a motor and gear into a single unit. In many instances such gearmotors require little more space than the standard motor. The motor itself operates at a standard speed but because of the gearing, almost any desired speed may be obtained at the pulley.

Table VII sums up very briefly the general characteristics and applications of the direct-current motor.

TABLE **VII** Summary of General Characteristics and Applications of the Direct Current Motor

Type	Starting Duty	Maximum momentary running torque	Speed regulation	Speed control	Applications
Shunt-wound constant speed	Med. starting torque. Varies with voltage supplied to armature, is limited by starting rest. to 125% to 200% full load torque	125% to 200% Limited by commutation	8% to 12%	Basic speed to 200% over basic speed by field control	Where starting requirements are not too severe. Centrifugal pumps, fans, blowers, wood and metal-working machines
Shunt-wound adjust. speed			10% to 20% increases with weak fields	Basic speed to 600% over by field control	
Compound-wound constant speed	Heavy starting torque limited by starting resistor to 130% to 200% full torque	130% to 260% Limited by commutation	Standard compounding 25% depends on amount of series winding	Basic speed to 125% over basic speed by field control	Drives requiring high starting torque and fairly constant speed. Pulsating loads. Shears, crushers, plunger pumps, etc.
Series-wound varying speed	Very heavy starting torq. Limited to 300% to 350% full torque	300% to 350% Limited by commutation	Very high with indefinite no-load speed	From zero to maximum speed depending on control and load	Drives requiring very high starting torque and where speed can be regulated. Cranes, hoists, bridges, car dumps, etc.

CHAPTER 16 Testing Motors

IT IS the problem of the designer to produce a motor which will perform with maximum efficiency. To keep a motor operating at this maximum, it is well to understand something about the losses which are inherent in the design and distinguish them from losses which may rise due to improper operation and maintenance.

Since every conductor offers a certain amount of resistance to the flow of current, and since in every rotating mechanism there is both bearing friction and windage, no electric motor can be 100 per cent efficient. The losses, as just indicated, may be broadly grouped into two general classes: electrical and mechanical.

Losses due to energy wasted in the form of heat caused by the passage of current through the motor windings are known as *copper losses*. These copper losses depend upon the resistance of the circuit and the amount of the current flowing through it. This heat loss is measured in watts and is commonly known as the I^2R loss. The term I^2R is derived as follows:

$$\text{Power (watts)} = \text{Volts} \times \text{Amperes} \quad \text{(by definition)}$$

Expressed in symbols, this relation is written

$$P = EI$$

Now, by Ohm's law, in a circuit containing resistance, the electromotive force E is equal to IR. Now, in the power equation above, replace the term E with its value IR. This gives

$$P = IR \times I, \text{ or } P = I^2R \tag{9}$$

Translated into words, all this means that the power consumed in the passage of a given current through a given resistance equals the square of the current times the ohmic resistance. The expression I^2R loss is referred to frequently in all discussions of motor losses and it is well to understand exactly what it means. In computing the I^2R loss of a direct-current motor, consideration must be given to the loss due to the current flowing through the brushes and across the contact area between the brush face and commutator, as well as the losses due to the current flowing in the motor windings. The brush-contact loss can be kept to a minimum by proper maintenance of the brush faces and the commutator surface.

Further electrical losses are due to the power consumed in changing the magnetic polarity of the armature core material as it moves from pole to pole while rotating, and the power losses due to the setting up of eddy currents in this core. These electrical losses are generally grouped together as core losses.

The mechanical losses are mainly frictional losses. There is always a certain friction loss in the bearings but proper lubrication will reduce this loss to a minimum. There is also another friction loss known as windage which is brought about by the air resistance on the rotating armature. A fan on the armature shaft, used to circulate the air within the motor, adds to this loss.

The efficiency of a motor is expressed as a percentage. Table V gave the approximate values of this for standard commercial motors. Efficiency is computed from

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}, \quad \text{or} \quad \frac{\text{output}}{\text{input}}$$

It is improbable that it will ever be necessary to compute the efficiency of a motor by measuring its input and output. For this reason it will only be given brief treatment here. The industrial analyzer previously mentioned will serve to measure the electrical input. Any voltmeter and ammeter of suitable range will do equally well. The input in horsepower is then computed from

$$\text{HP} = \frac{\text{volts} \times \text{amperes}}{746} \tag{10}$$

Accurate measurement of the power output of a motor is not quite so simple. The most common method is by use of the *prony brake*. One form of prony brake is shown in Fig. 59. A special pulley is placed on the motor shaft which is arranged for water cooling. This is necessary to prevent the pulley from becoming excessively hot during the test. Sometimes a pulley is arranged to permit a continuous flow of the cooling water but it is usually simpler to use one of hollow trough-like construction which is filled with water at the start of the test. Evaporation of the water dissipates the heat generated during the test. A band of brake-lining material encircles the pulley and is provided with a hand wheel to adjust the pressure. The end of the lever-arm is provided with a pivot which in turn rests on a scale. With the brake band tightened sufficiently so that the ammeter in the supply circuit indicates approximately full-load current, a reading is taken on the scale while the speed of the motor is measured with a tachometer. The power input to the motor is also measured by reading the meters in the supply circuit. The weight of the lever-arm must be subtracted from the gross weight indicated on the scale in order to obtain the net weight. From the data thus obtained, the output of the motor may be computed from the standard prony brake formula

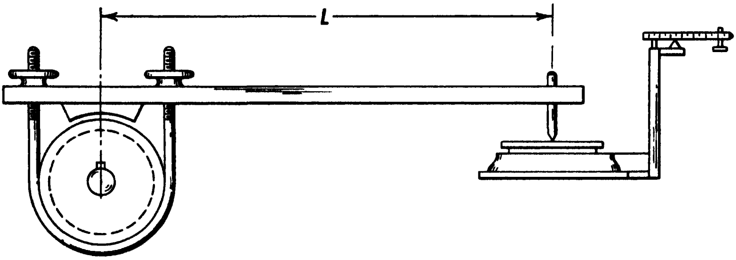


FIG. 59 The Prony brake. The lever arm should be kept horizontal by having the scale mounted at a suitable height.

$$\text{HP} = \frac{2 \times 3.1416 \times \text{Lever (in feet)} \times \text{pounds} \times \text{rpm}}{33{,}000} \qquad (11)$$

To simplify the calculation, the numerical constants in the formula can be combined

$$\frac{2 \times 3.1416}{33{,}000} = 0.00019$$

then the prony brake formula becomes

$$\text{HP} = 0.00019 \times \text{lever (feet)} \times \text{pounds} \times \text{rpm}$$

The size of the pulley used does not affect the test but it is important to determine both the tare and gross weights of the lever-arm so that the net weight will be accurate. The lever-arm should be kept horizontal during the test by having the scale mounted at a suitable height. With the horsepower output obtained from the prony brake test and the horsepower input obtained from the meters in the supply circuit, the efficiency of the motor can be easily computed.

Perhaps the most important test from the operating standpoint is that for *insulation resistance*. This test, when made at regular intervals, will afford a useful indication of the motor's electrical condition. It has as its objective the measurement of the resistance between the motor windings and its frame. Insulation resistance varies widely with the temperature, humidity, and cleanliness of the motor. When the value of the insulation resistance falls on successive periodic tests, it usually can be brought up to a satisfactory value by cleaning and drying the machine, provided, of course, no defect exists in the winding.

The test for insulation resistance is made with an instrument designed for this purpose, such as the megger insulation tester, vibrotest, megohmer, ohmmeter, etc. These are instruments calibrated to read resistance directly in megohms. A megohm is one million ohms. Most of these instruments are entirely self-contained, that is, they have their own source of power, no outside supply being needed. When using any of these instruments, it is important that the manufacturers operating instructions be carefully followed. It is also possible to use a high-voltage voltmeter for this test, provided a source of 500 volts d-c is available and the internal resistance of the voltmeter is known.

To measure insulation resistance by the voltmeter method, a reading of the supply voltage is taken and then a second reading with the insulation to be measured in series with the voltmeter. Insulation resistance can then be computed from

$$R_i = \frac{R_m(E - E_r)}{E_r} \tag{12}$$

where

R_i is the insulation resistance required.
R_m is the resistance of the voltmeter used.
E is the voltage of the supply line.
E_r is the voltage with the meter in series with the unknown resistance.

With the direct-reading instruments, the value of the insulation resistance is read directly on the instrument scale without the need for further computation. It is strongly recommended that a direct-reading insulation tester be kept on hand for periodic testing wherever motors are used.

Direct-current motors may be given an over-all test, or the armature, field coils, and brush rigging may each be tested separately. Before testing a motor, it must be completely disconnected from its power supply. This is important both for safety of the operator and to secure a true reading of the insulation value without damage to the instrument used. To make the test, after the motor is disconnected from the supply line, one terminal of the instrument (marked *G* on most testers) is connected securely to the frame of the motor. This is the ground connection. The other terminal is connected in succession to each of the motor terminals. The readings thus obtained are known as the over-all readings. With the brushes raised from the commutator surface, readings of the brush rigging, field coils, and armature may be taken separately. Should the over-all reading be low, the defect may be isolated by taking separate readings of each part of the motor.

There is some difference of opinion as to the minimum value of insulation resistance which is acceptable. Actually, the minimum value varies greatly with the type, size, voltage rating, age, and kind of insulating material used in the machine. New machines may have a lower value than older machines, due to the presence of solvents in the insulating varnish which are subsequently evaporated in normal operation. Many operating engineers feel that the insulation resistance of a motor should not be less than 1 megohm. The Standards of the American Institute of Electrical Engineers suggest that for a given machine, the minimum value of insulation resistance should be

$$\text{Insulation Resistance (Megohms)} = \frac{\text{rated voltage of machine}}{\text{rated KW plus } 1{,}000} \qquad (13)$$

but for fractional horsepower motors, the formula should be disregarded and 1 megohm used as the minimum acceptable value.

Insulation-resistance tests should be made at regular intervals as part of an established maintenance program, in order to obtain a true indication of the condition of the windings. Tests may be made monthly, quarterly, or semi-annually, depending upon the conditions under which the motor operates. Motors in damp or dirty locations should be tested more often than those in clean dry locations. Such periodic tests should always be made in the same manner, using a definite time duration, value of applied voltage, and under as nearly as possible the same conditions of temperature and humidity. A simple card form (one for each motor) should be provided to record the pertinent data each time the machine is tested. Such cards are available from the makers of the test instruments. Should comparison with values obtained from previous readings on the same machine under similar conditions indicate any large or abrupt decrease, immediate steps should be taken to locate and if possible, correct the cause so that complete breakdown of the motor can be avoided.

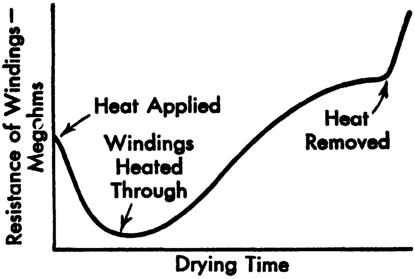


FIG. 60 Typical drying curve to show the variation of the resistance of the windings during the drying period.

Common causes of the abrupt decrease in the value of insulation resistance are: excessive dirt in the windings, moisture in the windings, and deterioration of the insulating material. Deterioration of the insulating material is usually the result of continual overloading of the machine.

The drying and cleaning of motor windings was discussed in Chap. 11. If the insulating material itself has deteriorated, complete rewinding is recommended. In some instances, painting or dipping the windings in insulating varnish, followed by baking, may save the windings and restore the value of the insulation resistance.

Test readings of the values of insulation resistance taken during the operation of drying and plotted as a curve appear as in Fig. 60. During the early part of the test, insulation resistance decreases because of an increase in the temperature and because the moisture is being driven out. When the temperature of the machine stabilizes, that is, when the windings are heated through, the insulation resistance rises because of the continued drying. When the rise in value begins to taper off, the heat is removed and the insulation resistance rises to a high value owing to the decrease in temperature of the machine. When a motor has been water soaked or submerged, it is recommended that readings be taken and recorded as in Fig. 60 during the drying process. If the motor does not respond to heat treatment, the condition of the windings and insulation should be thoroughly investigated.

If a low resistance ground has developed within the armature winding, it may be isolated by use of a low voltage current and a millivoltmeter. The connections are made to the commutator bars as indicated in Fig. 61. Here a line is connected from the meter to ground and the other meter connection is placed on one of the commutator segments. Both the supply and meter leads are then passed from segment to segment around the commutator. When a full delection of the meter is obtained, the coil under test is grounded. As a further check, measuring the ohmic resistance of the armature winding will sometimes reveal a wrong connection, which on a bar to bar measurement would normally give a uniform meter deflection all around the commutator. In taking such a set of resistance measurements of the armature, it is important to see that measurement is made from the proper set of commutator segments.

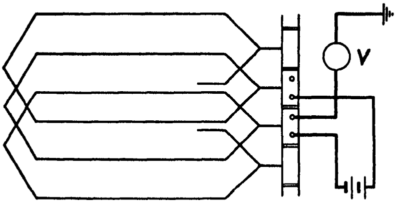


FIG. 61 Connections for testing a grounded armature winding.

A somewhat similar test for locating a faulty armature coil without removing the armature from the motor follows. All the brushes except two adjacent sets are lifted from the commutator. The two brushes remaining on the commutator are connected to a battery or other low voltage source. Leads of a sensitive voltmeter are applied to adjacent commutator segments. When there is neither an open circuit nor a short circuit, the reading of the meter should be the same between each pair of commutator bars for a particular path through the armature winding. If a coil is short circuited, there will be a zero voltage drop across the bars to which its terminals are connected. If there is an open circuited coil in one of the paths, no current will flow (through this path) and there will be a zero-voltage drop between each pair of commutator bars except the pair between which the open circuit is located, where the full battery voltage will be indicated on the meter.

Short circuited coils on moderate size motors can readily be tested by using a *growler*. This is an electromagnetic yoke excited with alternating current. In its common form, it resembles either a horseshoe magnet or the field pieces of a two-pole motor. The yoke is placed over a portion of the winding to be tested or if the armature is small, it may rest between the poles of the yoke. The yoke and the windings form an alternating-current transformer, with the yoke as the primary and the coil windings as the secondaries If there is a short-circuited turn or layer, the magnetizing current in the yoke winding will rise. If the current on the short-circuited section is maintained for a short time, the insulation on the short-circuited section will warm up appreciably or burn sufficiently to indicate the defective coil. Bar-to-bar readings in the manner previously described can also be taken while the armature coils are energized by transformer action of the growler.

If there is reason to believe that the insulating material within the motor has deteriorated, a high-potential dielectric test should be performed. It is recommended that such a test be conducted in a properly equipped service shop where proper safety precautions may be taken. The dielectric test should be applied between each electric circuit and all other electric circuits and metal parts grounded. No leads should be left unconnected during the test, as this may cause an extremely severe strain at some point of the winding. In making the test, the voltage should be increased to full value as rapidly as is consistent with its value being correctly indicated on the meter, and full voltage should be maintained for one minute. It should then be reduced at a rate that will bring it to one-quarter value or less in not more than 15 seconds. The standard test voltage, as recommended by the American Standards Association should be an alternating voltage whose effective value is 1,000 volts plus twice the rated voltage of the circuit to which the machine is to be connected.

It is sometimes necessary to run a temperature test to see that the actual operating temperature of the machine is below the maximum for the particular class of insulation which it contains. This is done by attaching thermometers to the hottest available spots on the machine. It is assumed that the *hottest-spot* temperature is approximately 15 C above the hottest accessible spot. Thermometers are fastened to the machine by placing the bulb in contact with the part and then pressing a lump of putty over it. The thermometer should remain in an upright position. Thermometers are placed on the main field poles, interpoles, connector straps, and bearings. The machine being tested should be protected from drafts of air issuing from adjacent machines which might effect the reading. The machine should be operated at rated load until all thermometers stop rising. It should then be shut down immediately and additional thermometers placed on the following parts: three on the commutator at each side; one at the outer end; one at the center; and one at the inner end. Four should be placed on the armature core on the tooth tops of the armature conductors where they issue from the slots. Four should be placed on the conductors in the end windings where they are not covered by binding bands; four should be placed on the binding bands themselves. This sounds like a lot of thermometers, but they are necessary in formal acceptance tests. For routine testing, a lesser number may be used. The highest reading of any thermometer on any one part should be considered as the temperature

TABLE **VIII** Limiting Observable Temperatures

Machine Part	Continuous-rated open-type general purpose 40C Motor		Intermittent-rated open-type; contin. or intermittent protected, dripproof and splashproof motors		Intermittent rated or continuous totally enclosed waterproof, dust-tight, and submersible motors	
	INSULATION		INSULATION		INSULATION	
	Class A	Class B	Class A	Class B	Class A	Class B
All windings other than those in next item	40C		50C	70C	55C	75C
Single-layer field windings with exposed uninsulated surfaces and bare windings	50C		60C	80C	65C	85C
Cores and mechanical parts in contact with or adjacent to insulation	40C		50C	70C		
Commutator or collector rings	55C		65C	85C	65C	85C

of that part. Table VIII gives the limiting observable temperatures for class A and class B insulation in various types of motors.

Mention should also be made here concerning the checking of the position of the brushes and brush rigging. This has been treated in detail in Chap. 10.

CHAPTER 17 Motor Troubles

SPEEDY diagnosis of motor troubles requires not only a basic understanding of motor principles, but also considerable practical experience in motor operation. Some difficulties are quickly recognized, while others can be identified only by having a thorough understanding of all factors involved. Special tests must often be made for the purpose of locating the source of the trouble. The instruments most useful in this work are the Megger insulation tester, the industrial analyzer, and the tachometer. The use of these instruments was discussed in Chap. 16. The electrician's trouble lamp is also handly for checking continuity of motor circuits.

If there is any unusual difficulty, it is helpful to measure the terminal voltage, the current consumption, and the speed of the motor, comparing all readings with the motor name plate data. This, of course, can only be done in cases where the motor actually runs. Such readings should be taken directly at the motor terminals to eliminate the control equipment.

It often happens that over a period of time, additional equipment is installed, thus gradually adding to the load of the motor. Eventually the time comes when the overloaded motor just gives up. It is important, therefore, to take into consideration any recent changes in load and operating conditions when motor troubles develop. Just because a machine ran freely before it stopped is no indication that it can be started again.

If the motor has been out of service for some time or if it has recently undergone repairs, difficulties in operation may then be due to errors in making internal connections or the repair work itself may have been faulty. If the motor has been in constant service and suddenly develops trouble, different causes should be looked for. However, it is not usual for motors in constant service to develop sudden trouble without previous warning. If the motor application is correct and if it has been

TABLE **IX** Motor Trouble Chart

Symptom	Possible cause	Suggested remedy
Motor will not start	No voltage at the terminals	Check power supply, look for a blown fuse, broken lead wire or connection, an open circuit in the control equipment, particularly in the resistors if there be any
	Overload	Check motor operation with load removed, if O.K. a larger motor may be required
	Bearing trouble	Remove load and try turning the motor alone by hand. If motor is frozen, look for a bad bearing or possible bent shaft. Check air gap between armature and pole pieces
	Armature circuit is open or shorted	Check brushes for proper contact with commutator. Check brush rigging and connections. Check armature coils as shown in Chap. 16
	Field circuit is open or shorted	Check field circuit. Isolate each field coil and check separately. Check polarity of field coils as half may be reversed
Motor tries to start but protective devices operate	Weak field or no field at all	Check field coils for open circuit. Check terminals of field coils for loose or broken connection. Check field control circuit, if any
	Torque insufficient to turn over load	Check supply for low voltage. Use a motor with better starting characteristics. Reduce load, if possible until motor attains speed
Running motor stops	Power failure	Check power supply, check fuses, controller and the protective devices
	Excess load	Check driven equipment to see if an excess load has been suddenly applied
Motor noisy	Shaft bumping on sleeve bearing motors.	Check alignment of drive. Check for end play in motor shaft. Check the bearing itself
	Excess vibration	Armature out of balance, should be dynamically balanced. Check bearings, loose, worn or rough bearings should be replaced
	Armature winding loose	Tighten winding in slots. Check banding of coils, look for high coils and drive down flush. Check clearance between armature

TABLE **IX** Motor Trouble Chart (*continued*)

Symptom	Possible cause	Suggested remedy
Motoı noisy (*cont.*)		and pole pieces. File face of pole piece or remove shim under base of pole piece if necessary
	Brushes chatter	Commutator surface may be rough or out of round. High mica on commutator, brush holders loose or brush springs out of adjustment
Sparking or flashing at brushes	Bad commutator condition	See Table III for details of brush troubles
	Brushes not set at neutral point	See methods of finding neutral point given in Chap. 10
	Motor overloaded	Reduce load or use larger motor
	Interpoles not properly adjusted	See discussion of interpoles in Chap. 7
Overheating of bearings	Misalignment	Realign motor and set. In all cases of bearing overheating keep shaft turning until bearing cools to prevent freezing
	Too much grease in ball bearings	Relieve supply to point set by manufacturer
	Sticking oil ring on sleeve bearing	Clean and free up ring to allow proper movement
	Insufficient lubrication	Lubricate regularly, follow manufacturer's instructions for proper lubrication
	Excess tension on belt or chain drive	Reduce tension to value recommended by motor or bearing manufacturer
	Bent shaft	Straighten shaft, check for original cause, drive may be faulty
	End shields not properly placed	Fit end shields squarely and properly tighten
	Motor not leveled properly	Level motor or if not possible, use a motor designed to operate in tilted position
Overheating of commutator	Incorrect brushes	See Chap. 9 for brush grades
	Severe sparking	Check position of brushes

TABLE **IX** Motor Trouble Chart (*continued*)

Symptom	Possible cause	Suggested remedy
Overheating of commutator (*cont.*)	Excessive brush-spring pressure	Check spring pressure and adjust in accordance with manufacturer's instructions
	Brushes off neutral	See Chap. 10 for finding neutral
Overheating of armature	Motor overloaded	Reduce load or use larger motor
	Vent ducts blocked	Clean out vent ducts
	Armature winding shorted	Check armature winding for shorts and grounds—Chap. 16
	Faulty bearings	Bad bearings may transmit heat to the entire armature
Overheating of field coils	Short circuit between layers	Check resistance of each field coil. Replace bad coil
	Excessive dirt on field coils	Clean coils, keep properly ventilated at all times
Motor runs too slowly	Line voltage low	Check line voltage. Check voltage of control circuit. Starting resistance not completely cut out. Check separate field control circuit, if any
	Brushes off neutral	See Chap. 10 for finding neutral
	Overload on motor	Check load on motor, check speed loaded and compare with load removed
	Excess current in field circuit	Check field circuit separately
Motor runs too fast	Field weak	Check for resistance in shunt field. Check field winding for shorts or grounds
	Brushes off neutral	See Chap. 10 for finding neutral
	High line voltage	Check with meter at motor terminals
Motor runs but does not develop full torque	Excessive friction	Check bearings and drive for mechanical resistance
	Incorrect line voltage	Check line voltage at motor terminals
	Brushes off neutral	See Chap. 10 for finding neutral

TABLE **IX** Motor Trouble Chart (*continued*)

Symptom	Possible cause	Suggested remedy
Motor runs but does not develop full torque (*cont.*)	Interpole polarity wrong	Check magnetic polarity of interpoles, particularly sequence relative to main field poles
Motor runs in wrong direction	Wrong connections	Check internal connections. Check field and armature circuits separately. Try reversing armature connections

given even reasonably good maintenance, most troubles can be avoided.

Once the trouble is properly diagnosed, the cure is usually routine. It is the purpose of this chapter to point out the possible causes of motor trouble and to suggest methods of effecting the cure. This can best be done in tabular form. Where the trouble has been previously discussed in the text, chapter numbers are given for reference. It is recommended that this chart be carefully studied so that the suggested remedy can be quickly found when the need arises.

CHAPTER 18 Reconnecting Direct Current Motors

THE expression "reconnecting motors" usually means the changing of the motor's internal connections in order to adapt it for a different operating condition, such as a change in the supply voltage or a different speed. Strictly speaking, the term "reconnecting" does not mean rewinding, although it works out in practice that in many cases the motor must be rewound before it can be reconnected. Not every motor can be changed economically, and consideration should always be given to the procurement of a new motor with the desired characteristics before undertaking extensive changes on an old motor. The condition of the insulation on the old motor is an important factor. If it is necessary to completely replace the old insulation, it is usually more economical to get a new motor.

The most common changes are voltage changes, usually to permit the motor to operate at half its original voltage rating or at double its rated voltage. An example is changing a motor rated at 230 volts to operate at 115 volts. Conversely, a motor designed to operate at 115 volts and be changed to operate on a 230-volt circuit. If the power output is to remain the same, then there must also be a corresponding change in the value of the current flow in the motor. Reducing the voltage from 230 to 115 will, of course, double the current. On the other hand when the voltage is doubled, the current is halved. An increase in current may call for a change of brushes in addition to any change that might be necessary in the motor winding. In order to maintain the magnetic field strength, a change in the value of the current means that a change must be made in the number of turns of wire on both armature and field. This is because the *ampere-turns* must remain an approximate constant.

Consider, for example, a shunt wound motor whose original voltage rating is 230. It is desired to reconnect this motor to operate at 115 volts. Assume the motor has four-field poles and four sets of brushes.

First, the field winding must be examined. It should be remembered that in the shunt-wound motor, the field circuit is connected directly across the supply line. In the original situation, 230 volts were impressed across the field circuit. It is now desired to secure the same field strength with the impressed voltage reduced to 115. If the four-field coils were originally connected in series as indicated in Fig. 62, it is merely a matter of regrouping the coils. In this figure, the voltage across each individual field coil is one-quarter of 230, or 57½ volts. By regrouping the coils so that two coils are in series and two such sets of series coils are in parallel across the supply line, there will still be 57½ volts across each individual field coil when the supply line is 115 volts These connections are shown in Fig. 63. If, on the other hand, the motor was originally connected as in Fig. 63, then all the individual field coils must be operating originally at 115 volts each. In this case, it is merely necessary to connect each coil in parallel, that is, each coil is connected directly across the new 115 volt supply line.

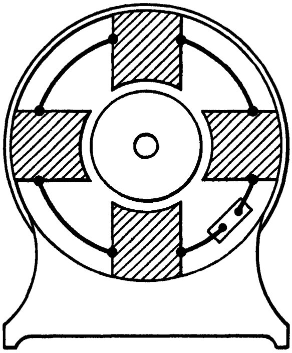


FIG. 62 Field coils connected in series.

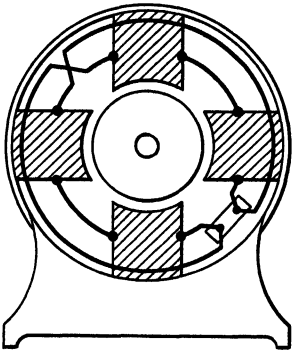


FIG. 63 Field coils connected in parallel.

Finally, if the individual field coils are found to be already connected directly across the supply line, they must then be rewound. The new winding must be designed so that the ampere-turns remain constant in order to preserve the full magnetic field strength. In any event, care must be taken in reconnecting the field coils so that the proper polarity relations exist around the motor. The polarity of each coil should be checked with a compass before the motor is placed in service.

The change in the armature circuit is exactly the same in theory, but in practice it is not so simple. Assuming the original motor armature to be wave wound with two parallel paths and four groups of brushes, by reconnecting into a lap winding with four parallel paths, the armature will function correctly at 115 volts. This means that the coil connections to the commutator must be changed. The difference between lap and wave winding commutator connections was explained in Chap. 6.

The basic idea is to reduce the number of turns in series by one-half when the applied voltage is cut in half. It is, however, not always feasible to change a wave winding into a lap winding, and before such changes are undertaken, it is well to have the armature winding carefully examined. For one thing, it means the bending of the end connections of the armature coils which are spread apart in the wave winding to a position close together, required by a lap winding. Old insulation may crack in doing this.

If the armature is already provided with a lap winding, it may still be possible to reconnect the coils to reduce the number of turns connected in series, but more often a complete armature rewind with one-half the number of turns and double the wire size is necessary. Armature windings are subject to so many variations that it is difficult to give general rules. Each individual armature presents a different problem.

When the armature is reconnected or rewound to operate at half the original voltage, the current which the brushes must carry is doubled. This may mean a change in either the size of the brush, the brush material, or both. On some motors there is not sufficient commutator space to increase the brush size. This should always be investigated in advance. The current-carrying capacities of motor brushes depend on both the brush contact area and the brush material. If brushes of the proper current-carrying capacity can not be fitted, the only alternative is to reduce the load rating of the motor. This may not be objectionable if there is sufficient margin between the actual driven load and the motor's rated load.

When motors are reconnected to operate at double voltage, the changes are reversed. The number of paths in series must be doubled both in the field circuit and the armature winding. If all the field coils are already in series, then complete rewinding of the field is necessary using twice the number of turns of wire with one-half the original cross-section area. The armature winding must also be carefully checked to determine the most feasible method of reconnecting the windings to double the number of series paths.

The limiting factor when reconnecting a machine to operate at a higher voltage is usually the bar-to-bar voltage on the commutator. Excessive voltage between bars may cause burning and flashovers. It is difficult to give rules concerning the maximum safe bar-to-bar voltage on commutators because of the number of factors involved. The thickness of the mica insulation between bars is one such factor. Motors provided with interpoles can usually operate at higher bar-to-bar voltages than noninterpole motors. On some motors, a bar-to-bar voltage as high as 30 may be perfectly safe, while on others, any voltage over 15 may cause trouble. The bar-to-bar voltage on noninterpole machines is generally between 5 and 20, while on interpole motors, it may be between 15 and 35 volts.

Where changes are made which increase the current flow within the motor, the current-carrying capacity of all windings, leads, and connections must be of sufficient size to handle the new current values without overheating. When the changes increase the voltage within the motor, a check must similarly be made on the condition of the insulation in all parts of the motor to prevent coil-to-coil breakdown to ground.

Reconnecting motors for a change in speed is less common than for a change in voltage. This is perhaps because of the variety of available control devices, which enable the speed to be closely regulated for various types of load. Speed changes can also be made by changing the size of the pulleys or gears by which the motor is connected to the driven load. Reconnecting the windings for a change in the rated full load speed of a motor usually also changes the horsepower output of the machine. For example, doubling the speed by suitably changing a wave winding to a lap winding will also double the horsepower output, provided the brushes and commutator can handle the increased current.

Since the speed of a d-c motor depends in part on the strength of the field, speed changes can be made by use of external resistors in the field circuit. When such a resistor is connected so as to be in parallel with the field coils of a series-wound motor, the speed can be increased above normal value. To reduce the speed of the series motor below rated value, a resistor may be connected in series with the motor. Because of I^2R losses in the resistor, such methods are very inefficient. In any motor, weakening the strength of the field will cause the speed to rise above normal and strengthening it will cause the speed to fall below normal. It is seldom practical to vary the speed by more than 25 per cent of normal by this method.

The speed of a d-c motor can also be changed by changing the air gap between the tips of the pole pieces and the armature. Increasing the air gap will weaken the effective field strength and increase the speed while reducing the air gap has the opposite effect. However, modern motors already have a minimum air gap and it is rarely practical to reduce it. A change in air gap will usually result in poorer speed regulation and reduce the motor's efficiency.

Speed changes can also be accomplished by reconnecting the armature winding. This usually requires a change in both the number of turns per armature coil and the wire size. Such changes are actually complete rewinding jobs and should be undertaken only by an experienced motor winder.

A series motor can usually be changed to function as a shunt-wound motor by merely changing the field coils. In order to keep the same magnetic field strength at full load, it is necessary to know the current and number of turns of wire on the original series field. New field coils are then wound which will have sufficient resistance to be connected directly across the supply line, either singly or in groups, without permitting excessive current to flow. The coils must also contain enough turns of wire so that the product of the new current times the number of turns will approximate the ampere-turns of the original field coils. Shunt coils will be more bulky than the original series coils and the space available must be taken into consideration in the design of the new coils.

It should be kept in mind that the basic idea in reconnecting motors is to achieve a balance between voltage, current, and coil turns which approximate the original values found in the motor. Economic considerations are the ultimate governing factor. Often a motor can be "traded-in" at a lesser cost than that of rewinding and reconnecting the original motor. As a rule, it is more economical to trade in small motors and reconnect large motors. However, when the required motor is not easily obtainable, it is well worth while to revamp the old motor. Only by obtaining comparative estimates of cost can an intelligent decision be made.

For a more complete discussion of this subject and for details of the design of new windings for changing the characteristics of existing d-c machines, the reader is referred to the following book: F. A. Annet and A. C. Roe, *Connecting and Testing Direct Current Machines* (New York, McGraw-Hill Book Company, 1937).

CHAPTER 19 Starting the Motor

When starting a direct-current motor, there must be some means to limit the initial inrush of current until the motor has reached a speed which will build up sufficient counter electromotive force to reduce the current flow to its normal value. Mention of this need has been previously made, and it will now be considered in more detail. Only simple starting devices will be discussed here. Combination starters and speed controllers as well as protective devices will be reserved for a later chapter.

Fractional horsepower d-c motors which come up to speed very quickly can be started by connecting the motor directly across the line. For this purpose, a simple switch is all that is needed, provided its contacts are large enough to carry safely the required current. Such switches are usually provided with an overload protective device to open the circuit in event of continued overload. Such devices will not operate at momentary overloads but function only when the overload is sustained. In some special instances, small integral horsepower motors up to 2 HP are started by connecting them directly across the full voltage of the supply line, but such instances are exceptional and not the rule. It is recommended that across-the-line starting be confined to motors under 1 horsepower. If a fractional-horsepower motor is so connected to its load that it can not come up to full speed quickly, it should not be started without a current-limiting device. Motors which are connected to their loads by gears should always be started slowly to avoid sudden shocks which may damage the gear train. Any high-inertia load should be started slowly to prevent overheating of the motor.

Frequency of starting is another consideration. Motors which are started and stopped every few minutes require a current-limiting device to prevent overheating of the armature winding due to the frequent inrushes of high-current values. This may not be necessary when the same motor is started only occasionally, say once every few hours. Constant starting will heat the commutator as well as the armature windings and will greatly reduce the life of a motor, unless it and its associated starting equipment are designed for this particular purpose.

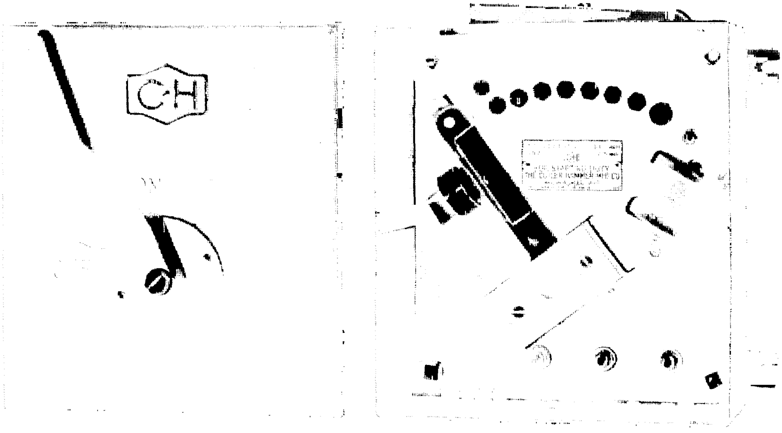


FIG. **64** Manual face plate type motor starter.
(*left*) cover with operating lever
(*right*) interior mechanism
(*Cutler-Hammer, Inc.*)

The fundamental object of any starting device is to limit the initial inrush of current in a motor. The starter should be so designed that the maximum current flow is not greater than 150 per cent to 175 per cent of the rated full-load current of the motor. This is accomplished by inserting blocks of resistance in series with the armature circuit which are removed step by step as the motor attains speed. These blocks of resistance have the effect of reducing the voltage in the armature circuit and are generally known as *reduced voltage* starters as opposed to *across-the-line* starters, which are full-voltage devices. The most common device for starting the d-c motor is the manual starting box, sometimes called a face-plate starter. Figure 64 shows a typical commercial manual starter. The wiring diagram for this starter is shown in Fig. 65. The connections as shown are for a compound-wound motor. Connections for the shunt-wound motor are identical except for the omission of the series field connection.

When the handle of the starter is moved to the right, it makes contact with the first two buttons, which are shown one below the other in Fig. 65. It is understood, of course, that the line switch has been closed. When the lever contacts the upper of the first pair of buttons, the shunt field is immediately connected directly across the supply line. Contact with the button directly below it connects the entire resistance of the starter in series with the armature circuit. By means of this arrangement, the armature always rotates in a full magnetic field.* As the lever is moved to the right from button to button, the resistance is gradually removed from the armature circuit. When all the resistance is finally removed, the operating lever rests against a holding magnet mounted along side the last button. This holding magnet is connected in series with the main-shunt field of the motor. The operating lever is provided with a heavy spring which will instantly return it to the off position if the holding magnet is de-energized. Failure of the power supply or a break in the motor field circuit will de-energize this magnet. In such an event, the lever automatically returns to the *off* position and the motor stops. It will remain stopped until again started by hand.

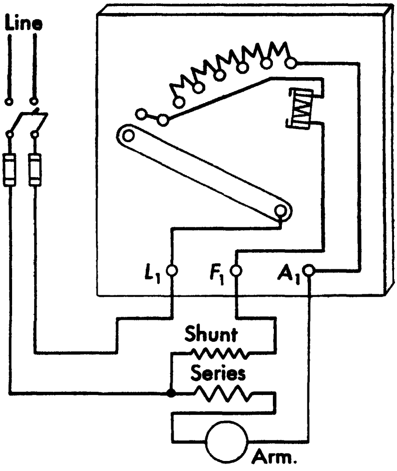


FIG. 65 Connection diagram of a typical manual starter.

In the larger size manual face plate starters, a double row of contact buttons may be used. A laminated bridging brush mounted on the operating lever makes contact between the rows of buttons. This is done so that the hand lever itself does not have to carry the armature current and therefore can be of lighter construction. Copper segments instead of small round buttons are also often used on the larger sizes to give a greater surface contact area.

The resistance coils built into the face plate type starter are designed for starting duty only. These coils can not carry the armature current for any length of time without overheating. In actual starting operation, these resistance coils are only in the circuit for a few seconds, for the operating arm is moved from contact to contact just as rapidly as the motor builds up speed. This arm can not be left in an intermediate position as the return spring will cause it to fly back to the *off* position.

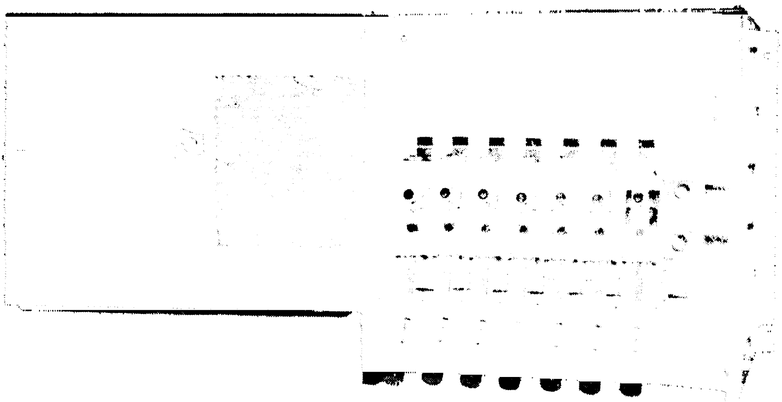


FIG. 66 Multiple switch type motor starter. Cover is open to show interior mechanism. (*Cutler-Hammer, Inc.*)

The operating arm must be brought in contact with the holding magnet at the end of its travel before it will stay put. In this position all of the resistance is out of the circuit. The face plate starter of this design is strictly a starting device. It is not intended for speed control.

The motor is stopped by opening the line switch. This causes the holding magnet to let go, and the operating arm, under pressure of the return spring, immediately flys back to the *off* position.

The face-plate type starter is limited in size by the current which it is able to handle without excessive arcing as the operating arm moves from segment to segment. For large motors with high-current requirements, a multiple-switch type of starter is often used.

The multiple-switch type mechanism, shown in Fig. 66, consists of a series of individual toggle switches, each operated by a separate lever. There may be any number of such lever switches in this type starter, but in most commercial forms, usually from four to eight are used, depending upon the size of the motor. The levers are closed individually, one at a time, as the motor comes up to speed. The closing of a lever switch removes a step of resistance just as the arm of the face place controller does as it slides from segment to segment. The switch levers are mechanically interlocked so that they can be closed only in proper consecutive order. The interlocks are further arranged that each lever must be held in position until the succeeding lever is closed. This means that two hands are required to operate this device. Closing the levers in consecutive order requires a hand-over-hand movement which introduces a time delay so that the levers will not be closed too rapidly. When the last lever has been closed, it is held in position by a magnetic latch. This magnetic latch serves the same purpose as the holding magnet of the face-plate starter. Current failure releases the last switch, and due to the interlocking arrangement, all other switches immediately open restoring the device to the original off position. The wiring diagram of this type starter is shown in Fig. 67. It should be noted that when the first switch is closed, the shunt field winding of the motor is connected directly across the line.

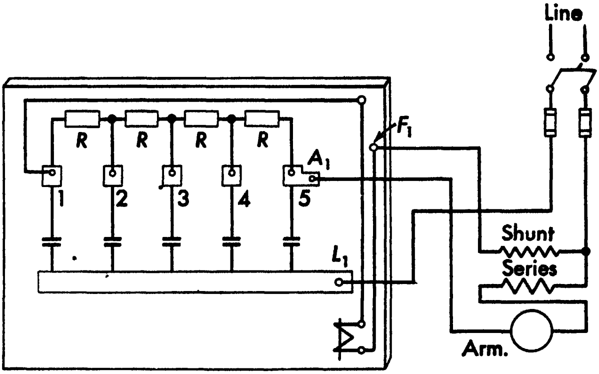


FIG. 67 Connection diagram of a typical multiple switch starter.

Another type of manual starter is the drum controller. This controller is generally used for speed control. It may, or may not, be provided with means for reversing the direction of the motor's rotation. Since this device is primarily a speed controller rather than a simple starter, it will be discussed in a later chapter.

When starting a motor from a distant point, a magnetic-type starter may be used. Magnetic starters, like manual starters, may be either across the line or of the reduced-voltage type The magnetic starter is sometimes called an *automatic starter*, since pressing a button will start the motor without any further effort on the part of the operator

The advantages of the magnetic-type starter over the manual type are numerous Magnetic control permits the installing of the power

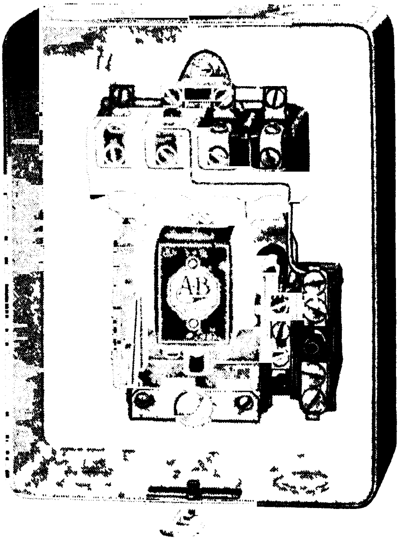


FIG 68 Solenoid type contactor (cover removed). (*Allen Bradley Co*)

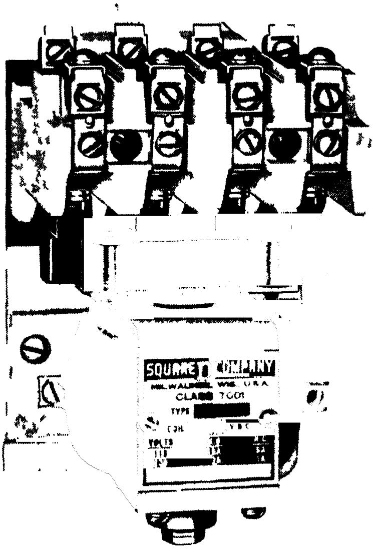


FIG 69 Solenoid type contactor (cover removed) (*Square D Company*)

contacts adjacent to the motor, allowing the control device to be located at a convenient distant point This often saves long runs of heavy power cable. The control circuit requires small wires as it carries only sufficient current to operate the magnetic circuit of the control device. Magnetic control also permits the control of one motor from several points, or the control of several motors from one central point. The magnetic controller can be actuated by automatic pilot devices such as a float switch, a pressure switch, or thermostat. The most important advantage, perhaps, is that of complete automatic control. Magnetic devices can be arranged to carry through a chain of operations in predetermined sequence without any attention from an operator.

In the simple magnetic across-the-line starter, only a magnetic contactor is used. The magnetic contactor should not be confused with the magnetic relay which may be similar in general appearance. The function of the magnetic contactor is to establish and interrupt an electric power circuit, while the magnetic relay is used to effect the operation of other control devices.

There are several commercial forms of magnetic across-the-line starters. In one popular form, the main contacts are closed by a solenoid operated plunger which operates vertically, while in other forms, the horizontal magnetic pull on an armature closes the main circuit.

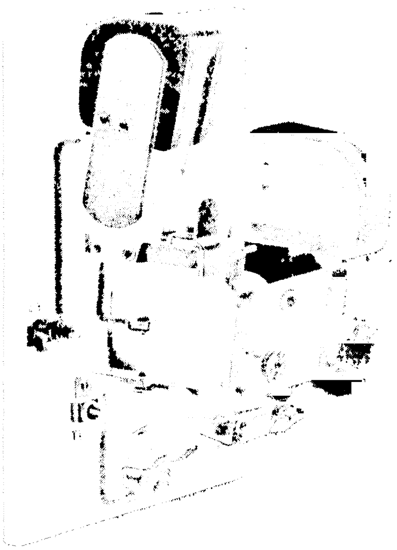


FIG. 70 Clapper type magnetic contactor with one arc shield lifted to show contact tips. (*Square D Company*)

Figures 68 and 69 show two commercial solenoid-type starters. When the solenoid is energized, the plunger moves upward and closes the power circuit by bridging the gap between the line terminals. When the solenoid is de-energized, the plunger drops by gravity and the circuit opens. By this arrangement, the circuit is opened in two places simultaneously, thus reducing the danger of arcing between contacts. It opens twice as quickly, so to speak, as a single contactor would open. The contacts are in the upper half of the device and are completely isolated from the operating coil. Operating coils are available for all standard voltages and are easily replaced in event of failure.

The moving-armature-type contactor is shown in Fig. 70. This is often called the *clapper* type. In the illustration one contact is shown with the arc shield lifted, while the other contact is hidden under the arc shield which is in normal operating position. Energizing the magnetic circuit draws the armature towards the magnet, thus closing the contacts. The illustration shows a double-pole contactor, but single-pole contactors are frequently used. A spring is incorporated in this type contactor to open the circuit quickly when the magnet is de-energized. The magnetic pull during the closing operation must be sufficient to close the contacts against this spring pressure. The armature carries a movable contact tip which closes against a stationary-contact tip mounted on the frame of the device. The tips are so mounted that they close with a wiping action to insure good electrical contact.

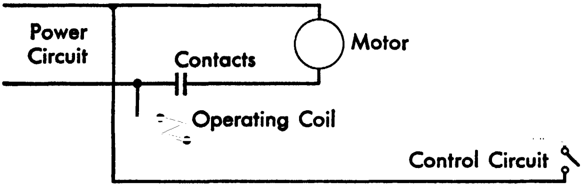


FIG. 71 Two wire control starter circuit.

The contactors of various makers differ in detail, but all follow the same general idea. Each maker claims technical superiority for his particular design. Those concerned with the selection of contactors should secure bulletins and catalogs from the leading manufacturers and from them select the type best suited to their needs.

There are two types of control circuits in general use for the across-the-line magnetic starter. The simplest of these is known as the two-wire control circuit. The diagram of this circuit is shown in Fig. 71. It should be noted that in wiring diagrams of control circuits, the operating coil is placed adjacent to the contacts it operates. In diagrams where this arrangement is not convenient, the operating coil and its associated contacts are indicated by similar numbers, for ease in tracing the circuits. In Fig. 71 only one side of the supply line is connected to the contactor which is of the single-pole type. A simple on-and-off switch operates the contactor. As long as this switch is closed, the contacts remain closed because the operating coil is energized. Opening the switch opens the contactor. In place of the switch shown in the diagram, any pilot control device such as a thermostat or pressure switch may be used. The control switch is sometimes in the form of a push button of the maintained-contact type. If, in this type circuit, the power supply fails, the contactor opens (either by gravity or spring) and immediately recloses upon the restoration of the power without any attention on the part of the operator. If the voltage drops to such a value that the magnet no longer has sufficient pull to hold the contacts closed, they immediately open and will close automatically when the voltage returns to normal. This is known as no-voltage *release.* It does not protect the motor from the return of the voltage, but merely releases it when the voltage fails.

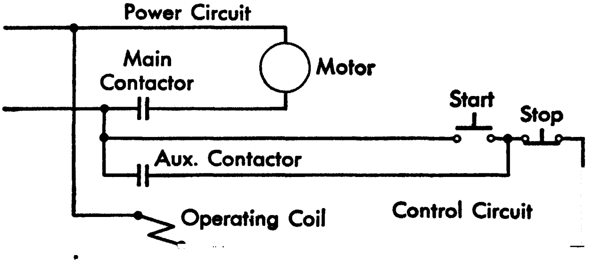


FIG. 72 Three wire control starter circuit.

To *protect* the motor from the return of the voltage, a somewhat different arrangement is used. This requires three wires in the control circuit and, in addition, the contactor must be provided with an auxiliary set of contacts for *holding* the control circuit closed. A close inspection of the clapper type contactor, shown in Fig. 70, will reveal a set of small contacts at the very bottom of the device below the operating coil. These small contacts are known as the auxiliary contacts. The diagram of the three-wire control circuit is shown in Fig. 72. The control circuit is energized by means of a start-stop push button. The start button is of the normally open type and closes the circuit only momentarily when pressed. The stop button is normally closed and opens the circuit momentarily when pressed. Figure 73 shows a typical start-stop button station with the cover removed. The motor is started by pressing the start button. This energizes the operating coil which closes both the main and auxiliary contacts. When the start button is released the auxiliary contact keeps the operating coil energized. Reference to Fig. 72 will make this clear. Pressure on the stop button breaks the operating coil circuit and both the main and auxiliary contacts open.

Should the voltage fall to a value that the operating coil no longer has sufficient pull to maintain contact, the circuit opens and the motor stops. When the voltage returns to normal, the motor does not start until the operator again presses the start button. This is known as *no-voltage protection.* The distinction between no-voltage release and no-voltage protection should be carefully noted. In the former case, the contactor merely releases on failure of the voltage and closes the circuit automatically upon its restoration. In the latter case, the motor is protected against the return of the voltage by making it necessary for the operator to press the start button.

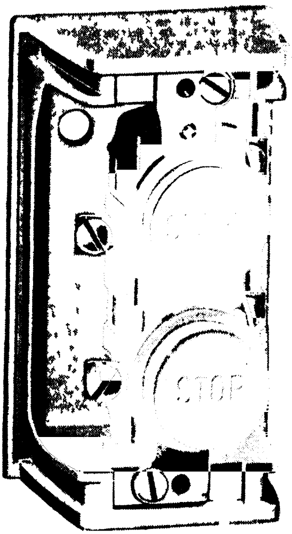


FIG. 73 Start-stop push button station with cover removed (*Allen Bradley Co*)

By extending the control circuit, any number of push-button stations can be connected in parallel, so that the motor can be controlled from any number of locations.

Since the use of the across-the-line type starter is limited to small d-c motors, the current which they are required to handle is comparatively small. When larger motors are to be started, some type of reduced-voltage starting becomes necessary. Here the magnetic contactor is required to interrupt currents of larger magnitude. This introduces the problem of extinguishing the arc which forms at the instant the contacts open.

The contactor must be designed to slam closed when the operating coil is energized. Once the contacts touch, they must not lose contact during the closing operation..A slight bouncing of the contact tips may cause an arc to form and may lead to the welding of the contacts together. Upon opening of the contacts, it is necessary to provide some means to extinguish the arc which forms at the contact tips. This is usually accomplished by artificially extending the arc to such a length that the line voltage is no longer able to maintain it. A common method of extending the arc is by use of a magnetic blow-out coil. This is a copper coil wound on a soft core and mounted close to the contact tips.

This coil is shown in Fig. 70 at the base of the open-arc shield. It is connected in series with the main contacts. Since the arc is actually a flow of current, it is surrounded by a magnetic field. The blow-out magnet is arranged to set up a magnetic field which will interact with the field of the arc in such a way that it exerts a force to cause the arc to move away from the contact tips. This greatly extends the length of the arc, and by so doing causes it to actually kill itself. The use of such blow-out coils is quite common on starting and control devices.

Basically, the operation of the reduced-voltage starter requires first the closing of a line contactor. This energizes the motor field by connecting it directly across the line. It also energizes the armature circuit through a number of blocks of resistance, all connected in series. Next, individual contactors or contact fingers close one at a time. Each of these removes one block of resistance from the armature circuit as the motor accelerates, until finally all resistance is removed and the armature is connected directly across the line. The removal of the blocks of resistance is accomplished by short-circuiting them with a contactor.

To remove blocks of resistance, one at a time, requires some type of time delay device. There are many types and kinds of such devices available. Only the more common will be considered here.

In one form, each contactor is individually provided with a dash-pot arrangement with a piston connected to the moving member of the contactor. When the operating coil of the contactor is energized, it exerts a pull on the piston of the dash-pot device, moving it slowly until it reaches the end of its stroke. At this point, the piston is freed and the contactor snaps closed. The dash-pot devices on each contactor are individually adjusted so that each closes in sequence after the proper preset time delay. This is known as a *definite time delay* device. No matter how slowly or how quickly the motor attains its normal speed, the dash-pot timer permits each contactor to close only after a fixed lapse of time.

In place of using individual contactors, each with its own dash-pot, often a multiple-arm contactor is used. In this form, a single dash-pot controls the movement of an arm on which several contact fingers are mounted. The contact fingers are so spaced on the moving arm that as the piston is released from the dash-pot, the fingers close one at a time in preset sequence. As each finger makes contact, a block of resistance is removed from the armature circuit. This is a very popular form, as only one time-delay dash-pot device is required for the complete starting operation.

In another form of definite-time-delay device, a clockwork gearing or escapement arrangement is used. When the start button is pressed, the closing of the contactors is delayed by the operation of the clockwork. As the gearing moves through its cycle, it closes the contacts one at a time in proper order to permit the motor to come up to speed. This is sometimes called the *tick-tock* time delay because of its resemblance to a clock-escapement mechanism. A somewhat similar device is the motor-driven starter, where a small pilot motor within the starter itself operates the gear train which snaps the contactors closed in proper sequence.

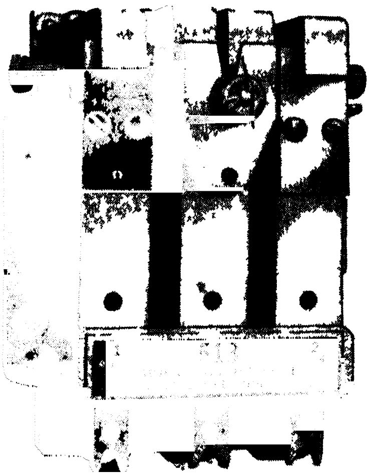


FIG. 74 Definite time accelerating relay. (*Cutler-Hammer, Inc.*)

Figure 74 shows another type of definite-time-delay device frequently used on machine-tool controls. This is a timing relay which controls the accelerating contactors. This timing relay is a simple magnetic device. It is operated by a condenser discharging through the magnetic coil. The time period is obtained by varying the air gap of the contacts.

It has been pointed out that as a motor increases its speed, the current taken from the supply line decreases. By the use of an arrangement of control relays, each designed to operate as the current through them falls to a predetermined value, contacts can be closed to remove blocks of resistance in fixed sequence. Here the time of operation depends on how rapidly the motor comes up to speed, rather than upon a definite lapse of time. In a somewhat similar form, the rise in counter electromotive force as the motor attains speed is used to control the starting circuit. Contactors for use in this type starter are wound with two coils; the windings are so connected that the magnetic field produced by one coil opposes that of the other coil at the instant of starting. As the motor builds up counter electromotive force, the force developed by the coil tending to close the contactor overcomes that tending to hold it open. By proper proportioning of the windings, the controller will close its contacts in proper sequence as the motor accelerates.

The definite-time-type starter is considered the most reliable and is used more often than any other type. Usually the direct-current motor comes up to speed comparatively quickly, and a properly set definite-time device will accelerate the motor uniformly and avoid excessive current peaks.

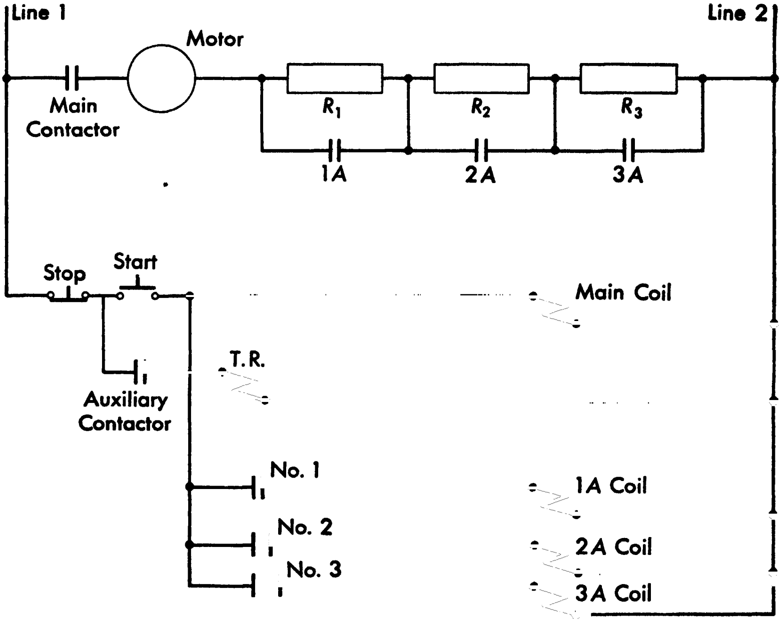


FIG. 75 Basic diagram of the definite-time-limit magnetic starter.

The basic diagram of the definite-time-limit starter is shown in Fig. 75. In this particular arrangement, a timing relay is used to close the contactors one at a time. The timing relay may be mechanical or of the dash-pot type; it makes no difference as far as the basic circuit is concerned.

When the start button is pressed (Fig. 75), the main coil of the con-
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tactor is energized. This operates to close both the main contactor and the auxiliary contactor. Closing of the main contactor starts the motor with three blocks of resistance in series with the armature circuit. The field circuit is omitted from the diagram. The closing of the auxiliary contactor starts the timing relay by energizing the coil *TR*. As the timing relay moves, first the contacts marked *No. 1* close. This energizes *coil 1A*, which closes the contacts marked *1A*. This action removes the first block of resistance R_1 from the circuit. As the timing relay continues, contacts *No. 2* close and *coil* A_2 is energized. This acts to close contacts *2A* and removes R_2 from the circuit. Finally, the last set of contacts marked *No. 3* close and *coil 3A* is energized. This coil closes contacts *3A*, removing the last block of resistance from the circuit, and the motor armature is connected directly across the line.

Should the power fail so that the main coil can no longer hold its contacts, both the main contacts and the auxiliary contacts open. When the voltage returns, the motor will not start until the start button is pressed. This starts the entire cycle over as all contacts will have opened on the power failure. Note that in Fig. 75 the contacts indicated as *No. 1*, *2*, and *3* are drawn an increasing distance apart. This is a convenient way to indicate that they close in rotation rather than all at one time.

In certain machine operations, it is desirable to move the driven machine slightly for the purpose of positioning a machine tool or to position the starting point of an operation. Machines in which strips of material must be threaded, may require a slight movement of the motor while the material is being guided through the machine. This is called *jogging*, or *inching*. Jogging, or inching, may be defined as the quickly repeated closure of the circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine.

In the magnetic circuit just described, pressure on the start button seals the main contactor and sets in motion the accelerating device. It is obvious that jogging can not be accomplished merely by repeated pressure on the start button. Even if the stop button were quickly pressed after the initial start, the machine would probably move too far. For these reasons, a special jogging button is added to the circuit where this operation is necessary. The jogging circuit must be arranged so that there is no possibility of sealing the main contactor when only jogging is desired. This is essential for the safety of those operating the machine. Figure 76 shows how the jogging push button is arranged to close the main contactor without sealing it. When the start button is pressed, the relay coil is energized. This closes the two relay contacts shown in the figure, which in turn energize the main contactor coil. When the start button is released, the main coil remains energized through the relay contacts and the regular starting cycle begins.

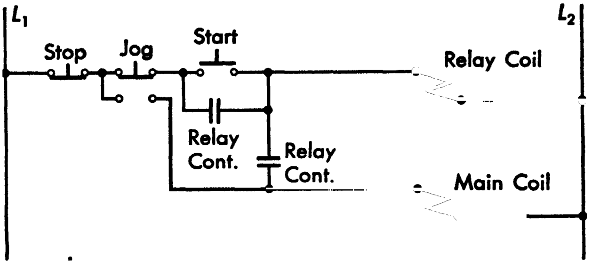


FIG. 76 Connection diagram of a typical jogging control circuit.

When the jogging button is pressed, the main contactor is energized directly. The relay is not energized and the relay contacts remain open so that there is no possibility of sealing the main contactor. The motor operates only as long as the jog button is held down. Push buttons for jogging have two sets of contacts, one set normally closed (the upper set in the diagram) and one set normally open.

This circuit substitutes a relay for the auxiliary contacts of the main contactor.

Motor protective devices are usually incorporated in the starter, whether manual or magnetic. These will be discussed in the next chapter.

The recommended number of starting steps together with an estimate of the maximum value of the initial inrush current for various sizes of d-c motors is given in Table X. It must be clearly understood that this table is only an approximation and that for any given motor application, the motor manufacturer should be consulted before starting equipment is selected.

It should be noted in Table X that no steps of resistance are indicated for a ½ horsepower motor at 230 volts. The average motor of this size has a full-load rated current of 2.3 amperes at 230 volts. When thrown directly across the line, the maximum-current inrush as estimated from the table would be 23 amperes. This is not considered an excessive value on most power circuits.

Starting resistors are usually designed to hold the initial-current inrush to about 150 per cent of the rated full-load current. This means that as the starting resistance is removed, step by step, the inrush current never rises (for any step) higher than 150 per cent of the full-load current.

TABLE X Starter Data

Horsepower at 230 volts	Number of starting steps	Max. current inrush expressed as per cent of full load current
½	0	1,000
3 to 5	1	450
7½ to 25	2	275
30 to 40	3	225
50 to 150	4	175

CHAPTER 20 Motor Protection

AN OVERLOADED motor is one which, over a considerable period of time, draws a current in excess of its normal rated current. Excessive current will heat the motor and if prolonged, will damage the windings. To protect a motor from heavy overload currents and yet permit the high value of current which, of necessity, must flow at the instant of starting, some very ingenious devices have been developed. Ordinary fuses are not well suited for motor overload protection, as they would interrupt the power supply every time the motor was started or if a momentary overload developed. Protective devices must be designed to permit the flow of large current values for short periods and to open the circuit should such excessive currents continue. This has been accomplished by the use of devices which incorporate some means of time delay.

There are two basic types of time delay devices in general use to protect d-c motors. One depends on the time required for a solenoid coil to lift an iron plunger; the other depends on the time required for the excessive current to heat a thermal element. Both types are found commercially in many varied forms.

In the solenoid plunger type, the time delay depends on the distance the plunger must travel before it causes the circuit to open. The distance is usually adjustable so that the time delay can be regulated to suit operating conditions. Where a comparatively long time delay is required, a dash-pot device may be added to prevent the plunger from moving too rapidly. The solenoid coil is designed to lift the plunger when a certain predetermined value of current has been reached. This solenoid coil is connected in series with the armature circuit and therefore carries the full armature current. When the current exceeds the preset value, the coil develops sufficient magnetic flux to lift the plunger. If the overload is of short duration, the plunger starts its movement but drops back before it is able to reach the end of its travel.

On a continued overload, the plunger completes its travel and operates a tripping device which opens the circuit. When equipped with a dash-pot retarding device, the time required to open the circuit may be inversely proportional to the amount of the overload. This means that the greater the overload, the more rapidly the circuit will be opened. A definite-time limit can also be arranged in some forms of this device so that regardless of the amount of the overload, the time required to open the circuit will always be the same. Since the overload device seldom opens the circuit itself but acts to open the circuit through the operation of some allied device, it is properly called a *relay*.

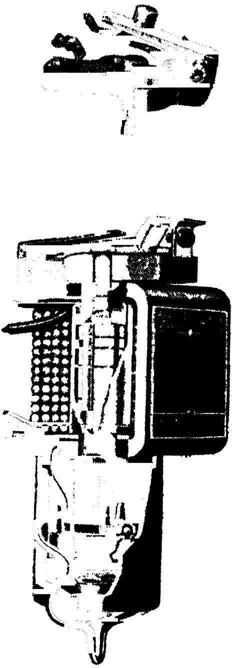


FIG. 77 Dash-pot type time delay relay. (*upper*) Interchangeable latching device to hold contacts open after plunger drops (*Allen Bradley Co.*)

Figure 77 shows an overload relay with a dash-pot time-delay device. In the main figure, an overload causes the circuit to open when the rising plunger separates the contacts located on the top of the device. Once the circuit has been opened, the plunger drops and the contacts close again. When this relay is modified by substituting the mechanism shown in the upper figure for the relay contacts, then the rising plunger trips a latch causing the contacts to open. Once opened, the contacts will not close again until reset by pressing the button on the top of the device. Both the automatic-reset and the hand-reset forms of the overload relay are widely used.

Thermal-overload devices, or temperature overload relays, as we shall now call them, depend on the physical change of certain materials under the influence of heat. A bimetallic strip will bend or a fusible alloy will melt when the proper amount of heat is applied. In both of these types, the required heat is obtained by passing the armature current through a small resistance popularly called the *heater*. At normal values of current, the heating effect is not sufficient to operate the relay, but when excessive currents flow the temperature is raised high enough to cause the device to function. Since time is required to heat the device to its operating temperature, the necessary time delay is achieved.

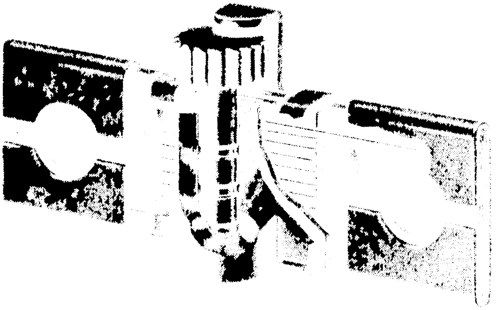


FIG. 78 Thermal heater element for use in thermal relay. (*Square D Company*)

In the usual form of bimetallic overload relay, the contacts are held closed by two strips of bimetallic material which act as latches. When the bimetallic strips bend sufficiently under heat, the latches release and allow the contacts to open. Heat is supplied to each of the bimetallic strips by a small coil or ribbon of a resistance material such as nichrome. Interchangeable heater coils are available, each calibrated to cause the bimetallic strips to operate at any required current value within the limits of the device.

The thermal element of the fusible alloy type of overload relay consists of a small metal tube filled with a special low melting alloy. A shaft extends into this tube and is firmly imbedded in this alloy. The external end of the shaft which projects beyond the end of the tube is provided with a small toothed wheel. The operating lever of the relay's latch, which permits the contacts to open, is held firmly against the toothed wheel by means of a spring. The heater coil surrounds the tube assembly. When sufficient current flows through the heater, the alloy within the tube melts and the shaft is free to rotate. The toothed wheel then turns under pressure of the spring, thus releasing the latch which opens the contacts. When the tube cools, the alloy hardens and the shaft is held tightly ready for use again. Figure 78 shows a cutaway view of a thermal element of this type. The complete latch arrangement of another make of thermal relay is shown in Fig. 79, where the tripping mechanism is clearly shown.

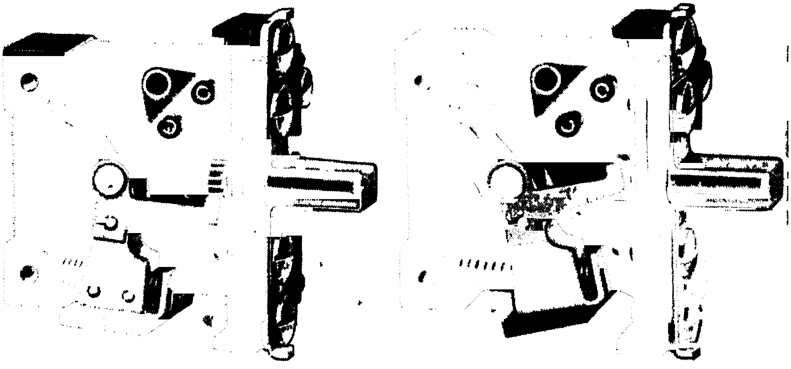


FIG. 79 Thermal relay trip unit.
(*left*) Contacts closed with pawl engaged in ratch of solder unit
(*right*) Contacts open with pawl released by slipping of ratchet
(*Allen Bradley Co.*)

The types of overload relays just described protect the motor at the controller. There is another type of overload device used chiefly to protect fractional horsepower motors which is mounted on the frame of the motor itself. This device is popularly known under the trade names of *fusetron* and *fustat*. They have the general appearance of the common household fuse plug. The fusetron is provided with a standard Edison screw base, whereas the fustat has a special tamper-proof screw base. The device is designed to be mounted in a special receptacle secured to the frame of the motor. It combines fuse protection with time-delay overload protection. Figure 80 shows the way the device is mounted on the frame of the motor.

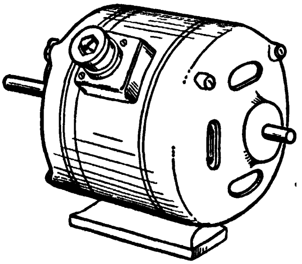


FIG. 80 Fustat mounted on a motor frame (*Bussman Mfg. Co.*)

A cross section of a fustat is shown in

Fig. 81. The thermal cutout of the fustat is imbedded in a low-melting alloy at its base with a coiled spring attached to its upper end. A link of fuse wire connects the thermal cutout with the external base of the screw plug. This plug screws into the receptacle on the motor frame. The receptacle is provided with a short rod which extends through the frame into the motor itself. Heat from the motor windings is conducted through the rod to the low melting alloy shown at *point 1* in Fig. 81. Should the motor winding overheat, the alloy melts and the spring pulls the cutout away from its contact with the base, thus opening the circuit. Should the motor draw excessive current, the alloy at *point 2* will melt. This likewise will cause the circuit to open. The link of fuse wire in this device is designed to withstand the starting current required by the motor, but should a direct short circuit develop, this fuse wire will immediately melt and open the circuit. This device affords three-way protection against overheating and short circuits. Like the common-plug fuse which it resembles, it is good for one-time protection only and must be replaced every time it operates.

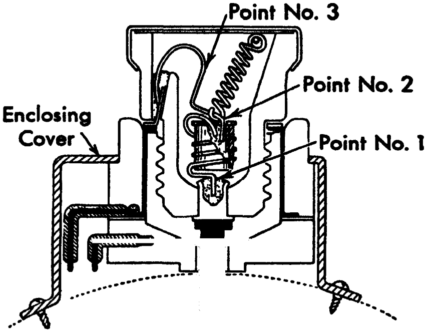


FIG. 81 Cross section of a fustat. Note the heavy pin (shown in solid black) which projects through the motor shell into its interior. (*Bussman Mfg. Co.*)

Quite separate and apart from the thermal overload protective devices, every motor should also be protected from short circuits. This protection may be either in the form of line fuses or a circuit breaker. In any event, short-circuit protection must not interrupt the circuit during the initial current rush.

Manual across-the-line (full voltage) starters are usually provided with some type of thermal-overload device. Since the use of such starters is limited to small motors, the motor itself may sometimes be protected as just described, in place of any protection within the starting switch. It should be understood that regardless of the size of the motor, it is essential that some form of overload protection be provided.

Reduced-voltage manual starters of the face-plate type are usually provided with a built-in overload relay. This may be of the moving-plunger type. In some instances, a moving armature replaces the plunger. Figure 82 illustrates the operation of a starter of this type. When the current reaches a preset value, the armature is drawn to the current coil, which closes a set of contacts (shown at h), which short circuits the holding magnet. The overload relay is shown as OL. The connections between the contacts K and the holding coil are not shown in the diagram. When the holding coil is short-circuited, the magnet releases the operating arm allowing it to fly back to the off position. Manual starters of this type are thus provided with both no-voltage and overload protection. Should either device operate, the motor is promptly disconnected from the power supply and will remain disconnected until again started by the operator.

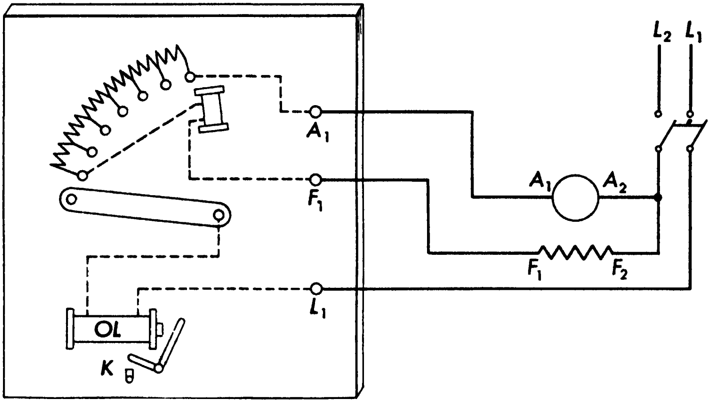


FIG. 82 Manual face plate starter with built-in overload relay.

Magnetic starters of the across-the-line type are nearly always provided with the thermal-type overload relay. It is usually incorporated as part of the starter itself. Interchangeable heater coils are available so that the thermal device will trip the contacts at any desired current value. A typical connection diagram of such a starter is shown in Fig. 83. Pressing the starting button energizes the main coil (M) of the contactor, which closes both the main contacts (MC) and the auxiliary contacts (AC). When the start button is released, the main coil remains energized through the auxiliary contacts. T_1 and T_2 are heater elements which are in series with the motor. On sustained overload, the heater element becomes hot, causing the thermal contacts (*TC*) to open. This de-energizes the main coil (*M*), causing all contacts to open. This disconnects the motor from the power supply. An examination of Fig. 83 will show that the thermal contacts (*TC*) are actually in series with both the auxiliary contacts (*AC*) and the stop button. The opening of the thermal contact has the same effect as pressing the stop button. This is the basic circuit of the thermal-overload relay. The relay unit may be either of the melting alloy type or the bimetallic-element type.

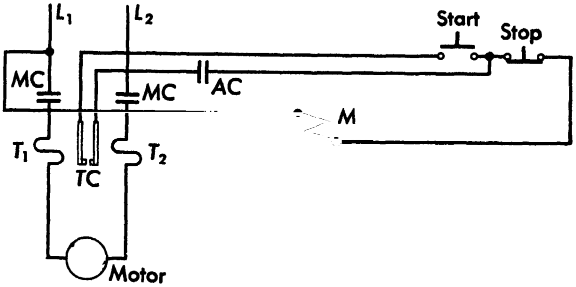


FIG. 83 Starter connection diagram with thermal-type overload protection.

Magnetic starters of the reduced-voltage type are similarly provided with the overload contacts in series with the control buttons and the heater elements in series with the motor-armature circuit. Figure 84 reproduces a portion of Fig. 75 to illustrate the connections of the heater elements and the thermal contacts. The heater elements, indicated as T_1 and T_2, function to open the thermal contacts (*TC*) on an

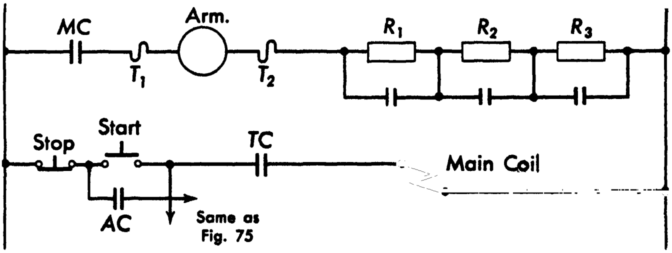


FIG. 84 Reduced voltage connection diagram with thermal overload protection.

overload. This de-energizes the main coil, which disconnects the motor from the supply line.

The diagrams shown here of the thermal overload-relay connections are basic and illustrate the general working principle. Each controller manufacturer varies the details of the circuit in accordance with his particular design practice. Most controllers are provided with a detailed wiring diagram, usually mounted on the inside surface of the controller cover. In addition, a table is usually provided listing the sizes and ratings of the available heater elements designed to function with the controller. This table gives the operating ampere-rating of each unit so that the best heater element for the application at hand may be selected. Heater elements should be chosen on a basis of the actual full-load current in amperes, rather than on the rated horsepower of the motor.

A heavy overload will sometimes cause the heater element to burn out in addition to functioning to open the circuit. It is therefore recommended that an extra set or two of heater elements for each size and type controller be kept on hand for use as spares. They are inexpensive and often not quickly available in the size and type required. Each spare heater element should be appropriately labeled so that in event of an emergency shutdown, the burnt-out heater can be quickly replaced with its proper counterpart.

Large d-c motors often require another form of protection. The opening of the field circuit may cause the building up of a high voltage which might puncture the insulation or otherwise damage the field windings. There is considerable energy stored in a d-c circuit which contains an inductance, and the field circuit of a large d-c machine is just such a circuit. It is therefore necessary to provide means for dissipating this stored energy when the circuit is opened. This is usually accomplished by connecting a discharge resistor across the terminals of the field circuit. If an ordinary fixed resistor is used for this purpose, it will consume power at all times and add to the operating cost. If such a resistor is inserted only on the interruption of the circuit, additional wiring and other attachments are required to perform the operation. The problem has been solved by the use of a discharge resistor made of a material called *thyrite*. This is a nonporous, inorganic, ceramic compound, which is practically an insulator at ordinary operating voltages, but is a relatively good conductor at very high voltages. The electrical properties of thyrite conform to a definite law. Each time the applied voltage is doubled, the conductivity of thyrite increases about 16 times. This increase in conductivity is automatic and instantaneous. Because of this unique property, it can be connected across the terminals of the field winding and left in the circuit permanently. When the field circuit is opened, the building up of a high voltage causes current to flow through the thyrite resistor and the stored energy is harmlessly dissipated in the form of heat.

CHAPTER 21 Stopping the Motor

AT FIRST glance, it would appear that all that is necessary to stop a motor is to disconnect it from the power supply. While all motors will eventually stop when the power is cut off, those driving high-inertia loads may run on for some time and those operating hoists and elevators will not stop until their load drops. Emergency conditions may also require prompt stopping to prevent serious injury to personnel or damage to equipment. Certain machining operations may require accurate stopping to avoid marring the work or to keep the tool from traveling too far. It is therefore apparent that some method of stopping or braking is just as important as the methods of starting the motor.

Braking may be accomplished by purely mechanical means, by purely electrical means, or, more often, by a combination of both. Straight mechanical braking is usually a manual operation in which the operator manipulates a foot pedal or hand lever to tighten a band on a brake drum. Electrical or electro-mechanical methods are usually automatic, or at least semi-automatic. It is these later methods which will be discussed here.

In the electro-mechanical type, a solenoid operating coil replaces the foot pedal or hand lever of the purely mechanical type. The mechanical equipment consists of the usual brake drum with shoes or bands to produce the necessary friction. The brake material is held tightly against the drum by means of a heavy spring, and it is the function of the operating solenoid to release the brake by working against the spring pressure. Figure 85(a) shows an old form of this type brake which is still in widespread use. The modern form is shown in Fig. 85(b). Strictly speaking, such a brake is electrically *released* and mechanically *applied*. Thus, in case of current failure, the brake is automatically set. On the other hand, the brake coil must be continuously energized while the machine is operating. Sometimes an electromagnet is used in place of the solenoid; the pull of the magnet on an armature acts to release the brake against spring pressure. While these two types differ in mechanical detail, the basic principles of operation are the same.

The coils on d-c brakes may be either shunt wound or series wound.

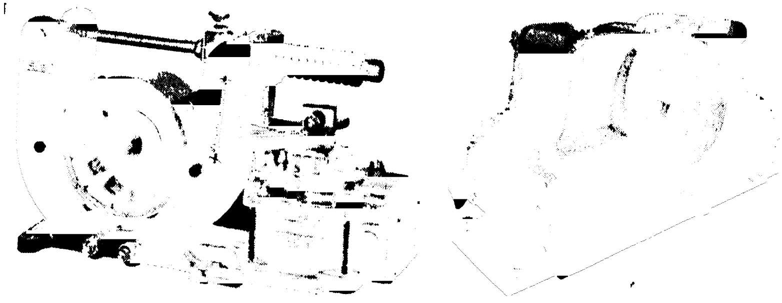


FIG. 85 Solenoid operated electric brake.
(*left*) open type, now obsolete
(*right*) modern crane type
(*General Electric Company*)

Shunt-wound brakes are connected directly across the supply line through an operating relay. The series-wound brake coils are connected in series with the motor. Choice between the two types depends on the application. The series-wound brakes are used mostly in crane operations, as they release the brake the moment the motor is energized and apply the brake when the power is cut off. The shunt-wound brake is more versatile, since its operating relay can be designed to operate in conjunction with other control operations, applying the brakes either promptly, or after a time delay, or as a function of the motor's speed.

In applications where the motor operates continuously for long periods of time, it is necessary to keep the brake coil continuously energized. This tends to cause the coil to overheat. To avoid this, solenoid brake coils are often provided with two windings. It is obvious that more energy is required to effect the release of the brake than is required to merely hold it open after releasing. The brake solenoid is therefore wound with a low-resistance coil to permit a high current to flow during the release operation, and a high-resistance coil to limit the current flow once the release has been effected. The two windings are in series with a contactor arranged to short out the high-resistance coil during the actual release operation. The low-resistance coil is known as the *pickup* coil; the high-resistance coil is called the *holding* coil. Figure 86 shows the arrangement of the two coils in series with a cutout switch across the holding coil.

In its simplest form, the shunt brake is connected across the line much like the shunt field of a motor. In Fig. 87, when the motor is energized by closing the main contactor (*M*), the brake releases. When the contactor (*M*) is open and the power cut off, the motor does not stop at once because of the counter electromotive force generated by the motor which continues to energize the brake coil. When the motor slows down so that the counter electromotive force can no longer maintain sufficient energy to prevent the brake from setting, the brake acts to stop the motor. When it is desired to apply the brake as soon as the power is cut off, two contactors are used, one for each side of the line as shown in Fig. 88. In this scheme, the brakes are controlled by contactor (*B*), which may operate in conjunction with the main contactor

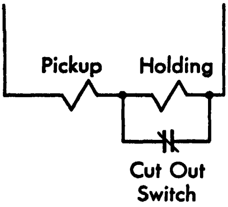


FIG. 86 Connection diagram for magnetic brake holding and pickup coils.

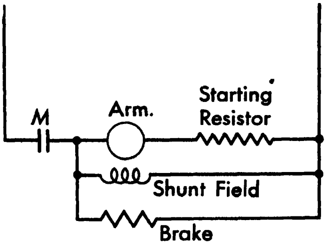


FIG. 87 Connection diagram for shunt brake circuit.

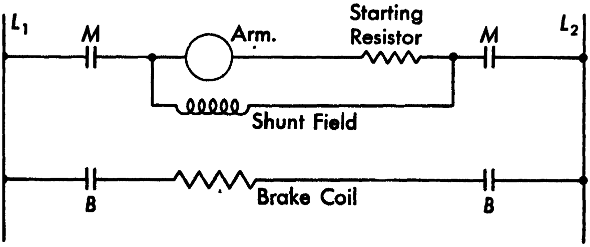


FIG. 88 Shunt brake circuit showing arrangement of two brake contactors.

(*M*) or be an entirely independent circuit. By this means, the brakes can be applied at any time in accordance with the application requirements.

Purely electrical braking methods are of three general types. These are dynamic braking, regenerative braking, and plugging. Electrical methods are often used in combination with solenoid or magnetic type mechanical brakes, for the purely electrical methods do not provide means for holding the equipment when disconnected from the power supply.

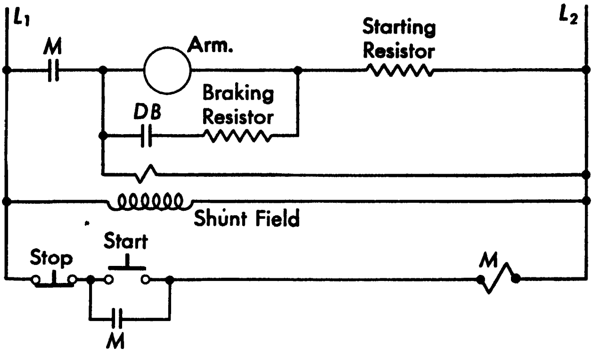


FIG. 89 Connection diagram for dynamic braking.

In dynamic braking, the motor actually becomes a generator. As such, it dissipates its energy through an external resistor which brings the motor to a stop. To accomplish this, the armature only is disconnected from the power supply and connected across an external resistor. The field circuit remains fully energized. At the instant dynamic braking is applied, the counter electromotive force of the motor causes a high current to flow in the resistor. This is because the armature is rotating in the motor's full magnetic field. As the motor slows down, the counter electromotive force declines, and the braking effect is reduced gradually. Thus, the slower the motor turns, the less the braking effect. Because of this, it is usually necessary to apply a mechanical brake to bring the motor to a final stop. A mechanical brake is also necessary to hold the motor at standstill. Dynamic braking is actually a decelerator rather than a brake. It is used mostly to prevent a motor from being overspeeded by a descending load under the pull of gravity. Figure 89 shows a typical circuit in which the dynamic braking contactor (*DB*) is used. Here, the opening of the main contactor (*M*) removes the armature from the line but not the field circuit. Closing the dynamic braking contactor (*DB*) places a block of resistance in series with the armature, while the field circuit is still fully energized. In many control circuits, pressing the stop button acts to first remove the armature circuit from the line, then close the dynamic braking contactor, and, finally, when the counter electromotive force falls to a certain preset value, a solenoid brake acts to bring the motor to a final stop.

Dynamic braking is generally used in connection with shunt-wound or compound-wound motors. It is possible to use dynamic braking in connection with series-wound motors by isolating the series field and then energizing it from a separate source of power during the braking operation. This complicates the control circuits and is therefore seldom done.

Regenerative braking is somewhat similar to dynamic braking, except that the counter electromotive force of the rotating armature is used to pump power back into the supply line. Electric cars and locomotives frequently use this method to decelerate with the addition of mechanical brakes for the final stop. Heavy trains on a descending grade often employ this method, as it returns considerable energy to the line, while preventing the train from attaining dangerous speed. This type of braking is also frequently used in connection with direct current variable voltage applications where speed adjustment is obtained by varying the voltage applied to the armature. These applications will be discussed later.

The final electrical method of braking is called *plugging*. This method brings the motor to a quick stop by reversing the direction of the current flow in the armature circuit. Normally, the current flow in the armature circuit is limited by the counter electromotive force generated by the rotating armature. This counter electromotive force is in a direction opposed to the impressed electromotive force from the supply line. At the instant of reversing the armature supply while the motor is rotating at full speed, the counter electromotive force and the new armature supply electromotive force are in the *same* direction. This means that the counter electromotive force adds to the supply voltage instead of opposing it. As a result, nearly double the starting inrush current would flow in the armature circuit unless steps are taken to prevent it. To hold the current to a safe value, a resistance is inserted in the armature circuit at the same instant as the current is reversed. As the original starting resistor is usually not large enough to

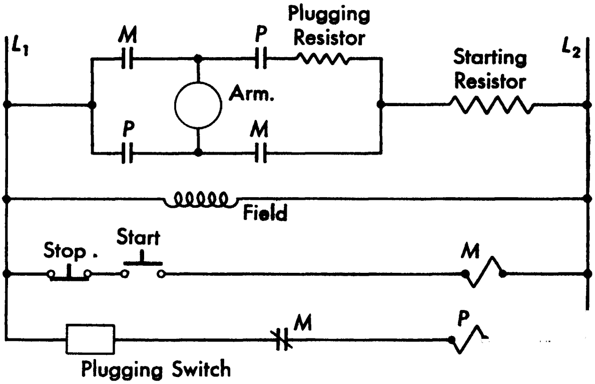


FIG. 90 Circuit diagram for motor plugging.

handle this double current, an additional plugging resistor is used. This requires a set of contactors to reverse the armature circuit and another set to insert the plugging resistor. An interlock on the main contactor prevents the plugging contactor from closing while the motor is in normal operation. Figure 90 shows the connections for reversing the armature circuit and inserting a plugging resistor. The plugging switch indicated in the diagram is a special rotating switch with a rotating element directly connected to the motor shaft. When the motor is running at rated speed, the rotating member of the plugging switch (operating at the same speed) holds a set of contacts closed. When the speed of the motor drops to a low value, the reduction in speed of the plugging-switch moving element permits the contacts to open. The action of a plugging switch is somewhat like that of a governor. In the arrangement shown in Fig. 90, the starting resistor is used in series with a special plugging resistor to limit the current flow. The opening of the main contactor (*M*) and the closing of the plugging contactor (*P*) reverses the direction of the current in the armature circuit and at the same time adds the plugging resistance to the circuit. When the motor comes to a near stop, the plugging switch automatically opens and the contactor (*P*) disconnects the motor from the line. If this were not done, the motor would start rotating in the opposite direction. The contactor in the plugging circuit (*M*) is shown as normally closed, that is to say, it is closed when the contactor coil (*M*) is de-energized. When the motor is running and the main contactor is energized, this contact is open and prevents the plugging contactor from operating.

Plugging is commonly used in connection with such applications as traveling cranes and certain types of mill equipment. It will bring the motor to an extremely rapid stop, but if it is desired to hold the motor after the quick stop, some type of mechanical brake must be used in addition. It is also obvious that the sudden stop brought about by plugging places a severe mechanical strain both on the motor and the driven equipment. For this reason, plugging is not always advisable and consideration must be given to all mechanical as well as electrical factors involved.

In most applications, a combination of an electrical method and a mechanical method of braking is required. The choice of the exact type or combination depends on the particular application. Controls involving combined electrical and mechanical braking are comparatively expensive, and the economic factor must also be considered. For these reasons, it is strongly recommended that the controller and motor manufacturer be consulted before making the final decision.

CHAPTER 22 Reversing the Motor

IT HAS already been mentioned that the direction of rotation of the d-c motor can be changed by reversing the direction of the current flow in either the armature circuit or the field circuit, but not both. This requires a complete separation of the armature and field circuits with individual terminals for each to facilitate making the necessary connections.

With the series-wound motor, it would appear that it makes very little difference whether the field circuit or the armature circuit be reversed, since the identical current flows through each. There are, however, certain advantages for reversing the armature circuit rather than the field circuit. In the case of the shunt- and compound-wound motors, the advantages of reversing the armature current are even greater than those of the series-wound motor.

One of these advantages is due to the fact that a field coil possesses a certain amount of self-inductance. This means that the opening of the field circuit during the reversing operation will usually require a special field discharge resistor in the circuit to prevent the building up of an excessively high voltage within the field coils. The field discharge resistor was discussed in the chapter on motor protection. Another reason for reversing the armature circuit rather than the field circuit is due to a certain hazard introduced by the use of contactors in the field circuit. A poor contact will weaken the field and cause the motor to increase its speed or even run away. Failure of the field contactor to close would be even more dangerous. In addition, any dynamic braking effect (due to the presence of the field) would be lost when the field circuit is opened. It is therefore common commercial practice to reverse the d-c motor by changing the direction of the current flow in the armature circuit. There are, however, certain special-purpose applications wherein it is advantageous to reverse the field circuit, so it should not be assumed that all motors are reversed by armature-current control.

The particular method used to reverse the armature connections depends to a considerable extent on the frequency of reversing the motor. Some motors require reversing only on rare occasions, while others must be reversed regularly as part of their normal operating cycle. Constant-speed motors may be reversed by means of a simple pole changing switch, while variable speed motors require a more complicated control system. The reversal of such motors will be considered more fully in the chapters on speed control which follow.

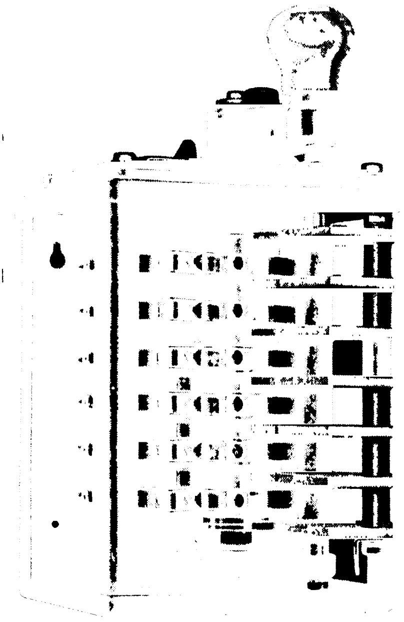


FIG. 91 Drum type reversing switch (cover removed). (*Allen Bradley Co.*)

It should be noted when reversing motors with interpole windings, that such windings are to be considered as part of the armature circuit and not the field circuit. The relation between the interpole circuit and the armature circuit must not be changed, or commutation troubles will develop. Some motor makers do not bring the terminals of the interpoles to the connection box on the frame of the motor for this reason.

In manual across-the-line starters for small motors, a simple drum-type reversing switch is often used such as that shown in Fig. 91. This is actually nothing more than a double-pole, double-throw switch in rotary form. With the handle of this type controller at the center or neutral point, the motor is completely disconnected from the line. Moving the handle to the right, causes the motor to rotate in one direction, while moving the handle to the left causes the motor to turn in the opposite direction. There is only a single point of contact in either direction. The internal connections of this type switch are arranged to reverse the current flow in the armature circuit without changing the field circuit. Since the handle must be moved through the off position when changing the direction of rotation, it is physically impossible to close both forward and reversing contacts at the same time. Miniature drum switches of this type are widely used for reversing small machines driven by fractional horsepower motors.

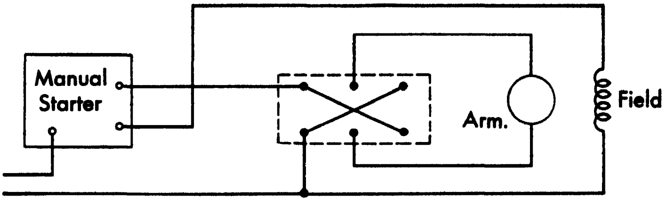


FIG. 92 Connection diagram for reversing a motor by means of a double-pole, double-throw switch.

Connections for reversing a motor with a manual face plate starter are shown in Fig. 92. The reversing switch is an ordinary double-pole, double-throw knife switch. It is connected between the starter and the armature of the motor. When using this method, the reversing switch should be locked so that it can not be thrown until the motor has been brought to a stop and the operating arm of the starter returned to the off position. This arrangement is recommended only where the motor is reversed infrequently. Should frequent reversing be necessary, some form of magnetic control is strongly recommended.

Reversing with a magnetic controller requires the use of three push buttons: forward; stop; reverse; and, in addition, some form of interlock, so that the forward and reversing contactors can not close at the same time. Since any contactor may, on occasion, stick or freeze, it is important that the interlock be positive so that there is absolutely no possibility for one contactor to close until the other has opened.

The basic diagram for a reversing magnetic controller is shown in Fig. 93. This diagram can be adapted either for across-the-line starting or reduced-voltage starting. In the diagram (*1F*) and (*2F*) represent a double-pole forward contactor operated by coil (*F*). The reversing contactors are indicated by (*1R*) and (*2R*) operated by the coil (*R*). These contactors are mechanically interlocked so that both can not close at the same time. Pressing the forward button energizes the coil (*F*), closing the forward contactors. They remain closed when the forward push button is released because of the auxiliary contactor, as has been previously explained. The closing of the forward contactor locks the reversing contactor so that it can not operate. Because of this, pressure on the reversing button while the motor is operating in a forward direction will have no effect. To reverse the motor, it is necessary to first press the stop button, which opens contactors (*1F*) and (*2F*) and releases the mechanical interlock on contactors (*1R*) and (*2R*). The motor can now be reversed by pressure on the reversing push button. Reversing while the motor is operating in a forward direction without the use of the stop button can only be accomplished by plugging, as described in Chap. 21.

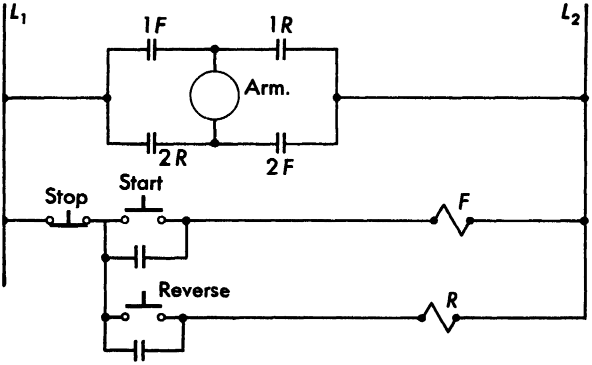


FIG. 93 Basic circuit diagram for a reversing magnetic controller.

It would appear that if the stop button and reversing button were pressed in rapid succession that the motor would be plugged. This is true when this arrangement is used with the across-the-line starter, but since this is used with small motors only, the inrush current would probably not be dangerous. With larger motors, pressing the reverse button re-introduces the starting resistance in the circuit, which limits the value of the inrush current.

Reversing the Motor

In some applications, such as a planer or hoist, it is desirable to stop the motor when the carriage or tool has reached the end of its travel. This is accomplished by the use of limit switches mounted at the point where the travel is to be stopped. In the case of a reciprocating operation, two limit switches are used, one at each end of the travel. The forward limit switch is connected in series with the forward contactor operating coil, so that when the end of the travel is reached, the limit switch opens, causing the contactors (*1F*) and (*2F*) to open. Pressing the forward button will no longer start the motor because of the open limit switch. Pressure on the reversing button will now start the motor in the opposite direction, causing the carriage to move away from the

FIG. 94 Time limit type starter with provision for reversing and dynamic braking. Compare the unit in the lower right corner with Fig 74 (*Cutler-Hammer, Inc*)

limit switch. The limit switch closes by a spring when the carriage moves away. The second limit switch, located at the opposite end of the travel, is similarly connected in series with the reversing contactor coil. In this arrangement, it is necessary to manually reverse the motor after the end of travel has been reached. A completely automatic arrangement, somewhat similar to plugging, can be used on a planer or similar machine tool, so that the carriage will start itself in the reverse direction after it has reached the end of its travel. Here the circuit is instantly reversed, first with a plugging resistor inserted to stop the motor and limit the current inrush, and then automatically removed to permit the motor to turn in the opposite direction. While such controls may appear complicated, they are actually nothing more than combinations of simple, basic, control circuits.

CHAPTER 23 Basic Speed Control

SPEED control of d-c motors is based on the fact that a motor tends to maintain a definite relation between the impressed electromotive force and the counter electromotive force. The impressed electromotive force can be varied by inserting steps of resistance in the armature circuit, while the counter electromotive force can be controlled by steps of resistance in the field circuit. Each method may be used separately or both methods may be used in combination. It should be mentioned at this point that inserting steps of resistance is not the only way to vary either the impressed electromotive force or the counter electromotive force. Other methods will be discussed later. In this chapter the discussion will be confined to basic methods only. When the two basic methods are combined, it is possible to vary the speed of the d-c motor over a wide range.

When the field weakening method is employed, that is, inserting resistance in the field circuit, a motor is selected whose normal rated full speed is the lowest required for the particular application. For varying speed by armature control, a motor is used whose rated speed will be the highest speed required. If both methods are used in combination, then a motor whose normal speed approximates the average required speed for the application should be used.

The face-plate-type manual controller is available for either method. There are, however, some basic differences in structural details between face plate controllers used for starting duty only and those used for speed varying duty. One important difference is the design of the resistors contained within the controller. Resistors used for starting duty only carry current for a few seconds during the actual starting operation. As the motor attains speed, the current passing through these resistors gradually becomes less and less. Because of this, resistors designed for starting duty are comparatively light and there is little need for providing means to keep them cool. Should such resistors be used for speed control, they would quickly overheat and burn out. Resistors for speed-control duty are considerably heavier in construction, well-ventilated, and designed to call the full-load current continuously. Such resistors, because of the I^2R loss, may get quite hot when called upon to

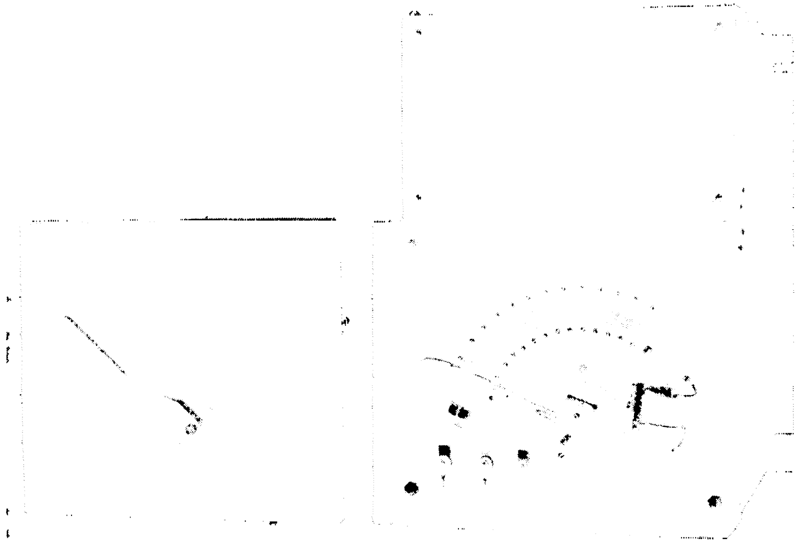


FIG. 95 Manual face plate type motor speed controller.
(*left*) cover with operating lever
(*right*) interior mechanism.
(*Cutler-Hammer, Inc.*)

carry the motor current continuously and must be well-ventilated to properly dissipate this heat. It is important, therefore, to select resistors designed for speed control and not starting duty if they are to be so used. Resistor and controller name plates are usually marked to indicate the duty for which they are designed. Another important difference is in the design of the operating lever mechanism of the controller. When a face-plate controller is designed for starting duty only, the operating lever can not be left at an intermediate position, as the spring will return it to the off position. When such a controller is designed for speed control, provision must be made to allow the operating arm to remain in any position and yet spring back to the off position in event of current failure. There are a number of methods of accomplishing this.

One method is shown in Fig. 95. Here the operating lever has a toothed segment at its lower end. A latch, held in position by the holding magnet, engages with the teeth so that the lever will remain in any desired position as long as the holding magnet is energized. The teeth are shaped similar to a ratchet so that the handle can be moved forward easily but will not slip back. Should the current fail, the magnet will release the latch and the operating arm will spring back to the off position. This type of controller is used both for starting and armature circuit control. When the operating lever is at the full-speed point, the motor is connected directly across the line and operates at its normal full-load speed. At any intermediate position of the lever, the motor will operate at a lesser speed. It is not possible to make the motor go above rated speed with this type controller.

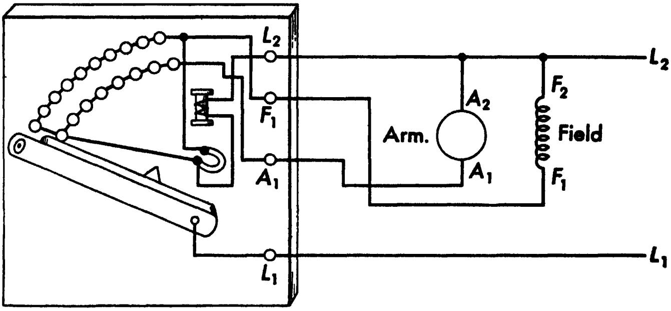


FIG. 96 Compound starter connection diagram.

The starter used for field circuit control is known as a compound starter and is considerably more complex in construction. Such a starter is shown in Fig. 96. The operating lever of the compound starter is actually two arms in one unit, arranged one directly over the other. Moving the operating handle in a clockwise direction moves both arms as a unit and starts the motor by gradually removing steps of resistance from the armature circuit. Since this starter is not provided with the toothed wheel and latch arrangement of the previously described starter, it can not be left in any intermediate position. When the motor reaches full rated speed, the operating arm contacts the holding magnet. This magnet holds only the under portion of the compound operating lever so that the upper portion can now be moved back in a counterclockwise direction, that is, towards the original off position. As this arm moves counterclockwise, steps of resistance are inserted in the field circuit and the motor speed increases above rated speed. During the starting period when the compound lever is being moved

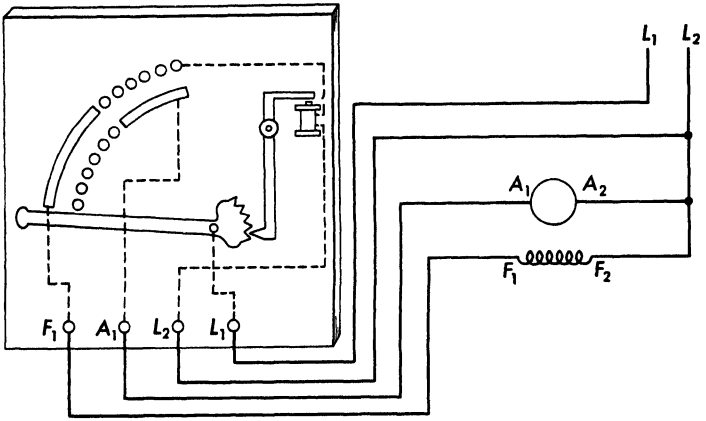


FIG. 97 Manual face plate controller combining armature and field control.

clockwise, the field resistance is shorted out of the circuit by the U-shaped contactor shown in the figure. This is necessary to insure a full field during the starting period. A small wedged-shaped insulator on the lower arm of the compound unit forces this contact open when the motor attains full speed. This removes the short circuit from the field resistors so that they can now be inserted in the field circuit as the upper arm is moved back towards the original off position. Should the current fail, the holding magnet releases the lower arm unit which immediately flies back to the off position carrying the upper arm along with it. In Fig. 96, the inner row of buttons are steps of the starting resistance while the upper row are steps of the field control resistance. It should be kept in mind that the compound operating arm moves as a single unit during the starting period only and that the upper part moves thereafter for speed control. This form of starter is suited for applications where speeds above normal are desired.

Another basic type of face-plate controller combines both armature and field control in a single unit. Such a starter is shown in Fig. 97. This starter is provided with a single operating arm and during the first half of its travel removes resistance from the armature circuit while the field circuit is fully energized. After passing the halfway point, the arm inserts resistance in the field circuit. A toothed segment and ratchet arrangement is provided to permit the operating lever to remain in any desired position. Current failure will release the arm, which will immediately return to the off position. During the first half of the lever-arm movement, the motor runs at a speed lower than its normal rated value, while during the last half of the arm movement, the motor runs at a speed above its normal rating. It should be repeated that the resistors used in controllers of this type are designed to carry the required full-load current continuously without overheating.

The most versatile of all manual speed controllers is the *drum controller*. This is basically a drum or a cylindrical surface mounted on a shaft which is free to rotate. On the surface of the drum a number of conducting segments are mounted. These segments may or may not be connected with each other, as desired. Flexible contact fingers, mounted on a stationary frame, are arranged to make contact with the various segments as the drum is rotated. By properly spacing and mounting the individual segments on the drum surface, contacts can be made in any sequence. The linear length of the segments can be varied to change the duration of the contact. No external connections, either from the line or from the motor, are made directly to the moving drum. The segments themselves are connected as desired to function to complete the circuit by making contact between two or more of the stationary fingers. The segments on the drum surface are thus nothing more than jumpers which bridge the stationary fingers.

The drum shaft is provided with a star wheel with a fixed roller so placed that it will ride over the star wheel notches. This roller is held under tension against the star wheel by means of a spring, to insure the stopping of the drum in definite fixed positions. In this way the desired segment or group of segments, will be held in position to make proper contact with the stationary fingers and the operator can readily feel each speed position as he moves the operating handle. This type controller will perhaps be remembered as the old street-car controller. Figure 98 shows a typical drum controller with the cover removed.

The drum controller is more rugged than the face-plate manual controller and will stand greater abuse from an unskilled operator. Because the fingers can be adjusted to press heavily on the moving segments, the drum controller can handle higher current values than the face-plate type. It can also be provided with individual blow-out coils at each finger to reduce the arc to a minimum as the drum is rotated. Complicated circuits can be easily handled by the drum controller merely by suitably arranging the segments and contact fingers. Drum controllers may or may not provide for reversing the motor.

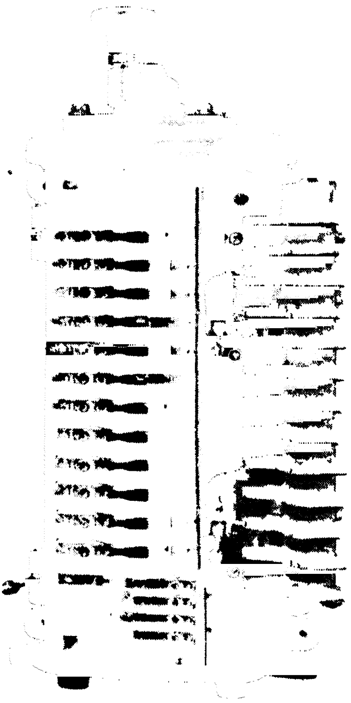


FIG. 98 Manual drum controller with arc chutes swung to the right to expose contacts. (*Cutler-Hammer, Inc*)

The standard form of wiring diagram for a typical drum controller is shown in Fig. 99. To the uninitiated, this diagram may be a little difficult to comprehend at first glance. It can best be understood by examining the rotating drum alone, which is shown in Fig 100. This drum is shown with a number of segments mounted in its surface. The heavy dots to the right, numbered 1, 2, 3, ... represent the points of connection between the external circuit and the stationary fingers. The fingers themselves are represented in this sketch by the straight lines between the numbered dots and the segments on the drum surface. In the figure, the line connected to terminal *1* is making connection (through the stationary finger) with the first segment on the drum surface. The last two fingers are also making contact with the long segments at the lower part of the drum. The fingers in between are not making any contact with the drum in its position shown in the sketch. It is obvious, however, that as the drum is rotated, the other segments will make contact as they come into position. Note also that there are connections between the segments themselves on the surface of the drum. Once the idea of this sketch is understood, the standard wiring diagram becomes clearer.

In the standard wiring diagram, Fig. 99, the line terminals are represented by a row of heavy dots down the center. These dots also represent the stationary fingers. It is to these terminals that all external connections are made. The dashed vertical lines indicate positions of the drum for each successive step as it is rotated. The heavy lines indicate the electrical connections between segments on the surface of the drum. The resistors, shown at the far left, are mounted separately outside of the drum. To trace the connections for any position of the drum, it is merely necessary to follow the particular vertical dashed line numbered to correspond with that position. For example, in position *forward 3* tracing down the dashed line under number three on the forward side, contacts are made with R_3, R_2, R_1, *1*, *2*, and *4* and their respective fingers. In another example, suppose it was desired to trace the armature circuit when the controller is at the first forward position.

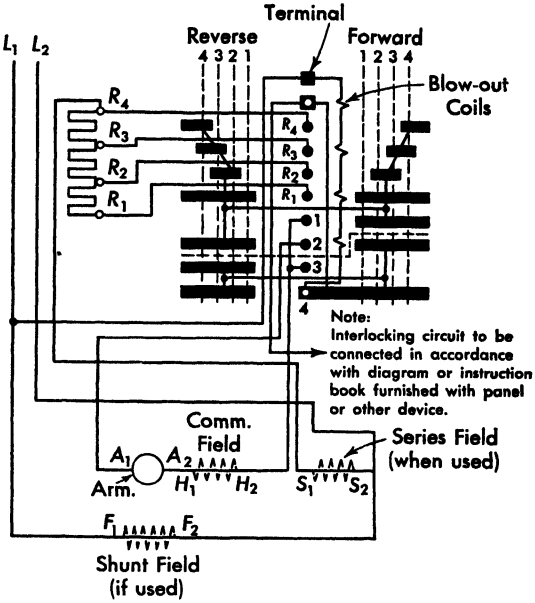


FIG. 99 Typical conventional diagram for a drum controller. (*General Electric Company*)

Starting at the armature terminal A_1, it will be found that this connects with finger *2.* In the first position forward a segment contacts finger *2.* This segment is connected to the lowest segment which contacts finger *4.* Tracing through finger 4, the circuit leads through the blow-out coils to the terminal to which line *1* is connected. Next, starting at the other armature terminal A_2, it will be noticed that this connects with two fingers, *1* and *3.* However, since there is no segment to engage with finger *3,* it can be disregarded. Finger *1* connects with a segment which in turn is connected to the segment directly above it. This upper segment engages with finger R_1. Tracing the path from R_1, the circuit leads through all the resistor steps, then through the series field (if there be one) and finally to L_2, which is the other side of the supply line. The diagram shown can be used for either shunt or compound wound motors, and the connection for each field winding is indicated.

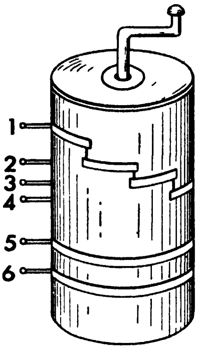


FIG. 100 Elementary rotating drum. The numbered fingers make contact with the surface segments as the drum rotates.

The drum controller alone affords no protection from current failure as does the face plate controller. To secure proper protection both from current failure and overload, auxiliary relays are necessary. These are usually mounted in a separate enclosure popularly known as the *protective panel.* This protective panel is considered an essential part of a drum controller installation. Contactors and relays can be arranged so that in event of current failure, it is necessary to return the controller handle to the off position before the motor can be started after the return of the power supply.

Despite all the advantages of the drum controller, it also possesses certain disadvantages. Since the fingers press heavily on the sliding segments, there is considerable wear which eventually causes excessive arcing as the drum rotates. Also, when turning the drum, the separation between the segments and the fingers takes place comparatively slowly, again introducing arcing. This arcing gets progressively worse as the wear continues. In an effort to overcome these inherent faults, a *cam controller* has been produced.

The cam-type controller is similar in external appearance to the drum controller. The internal mechanism, however, is quite different. In place of the stationary fingers, a set of contactor units are provided. These contactor units are held open by means of individual springs so that each contactor is normally open, that is, no connection between the two sides of the contactor is made. Each individual contactor unit is provided with a short lever arm so arranged that pressure against this lever arm will close the contactor. Cams mounted on the rotating member in place of the sliding segments of the drum controller are so positioned that they press on the lever arm of the contactor units as the shaft turns. This pressure closes the contactor. By suitably positioning the cams on the rotating shaft, the individual contactors can be made to close in any desired sequence and remain closed for any desired duration. These contactor units are designed to open with a snap as the moving cam leaves the lever arm, thus reducing the arcing and burning. Individual contactor units are easily renewed, thus mechanical wear and electrical wear are completely separated. This wiring diagram of the cam-type controller is the same as that of the drum controller.

Controllers of both the cam and drum types are considered as manual controllers, since the full motor operating current passes through them and is controlled by the movement of the handle. In the case of magnetic control, a small and lighter controller replaces the heavy standard drum controller. This is called a *master switch.* The essential difference between a master switch and a drum controller is that the former handles only the control circuits, while the latter carries the entire full-load motor current. A separate panel on which the various magnetic contactors and relays are mounted, together with the necessary resistors, is usually located close to the motor, whereas the master switch is placed to suit the convenience of the operator. Movement of the master switch actuates the magnetic contactors in the desired sequence. Time-delay devices may be introduced so that the timing of each step of speed control is independent of the rapidity with which the operating handle is moved. Overload and no-voltage protective devices can be included and so arranged that the master switch must be returned to the off position before the motor can be restored to service. There are many types of highly specialized control circuits involving the use of a master switch with a considerable number of contactors and relays. These are beyond the scope of this book.

With either the drum controller or the master switch, speed control of the motor is achieved by inserting or removing steps of resistance in the armature or field circuits in a manner similiar to that described in the discussion of the face plate controller. The use of such resistors involves certain losses in the form of heat, which in turn reduces the over-all efficiency of the control system. The required resistors are often bulky and require considerable space. They must also be adequately ventilated. Maintenance costs also increase as the number of auxiliary devices (contactors, relays, protective devices, etc.) increase. These factors become very important in the case of large installations. Introduction of resistance in the motor circuit also adversely affects the speed regulation of the motor. These drawbacks have led to the development of other methods of control based on varying the supply voltage to the motor.

CHAPTER 24 The Direct Current Generator

THE direct current generator plays an important role in many systems of variable-voltage speed control. A basic understanding of the d-c generator will be helpful in following the speed-control circuits of such systems.

A generator is a machine which converts mechanical energy into electric energy. It is nothing more than a motor in reverse. Actually, most d-c motors can be operated as generators by merely driving them from a source of mechanical power. A generator makes use of an important fundamental electrical principle: When a conductor passes through a magnetic field, an electromotive force is set up, or *induced*, in that conductor. Figure 101 shows an elementary d-c generator. Here a single loop of wire is rotated in a magnetic field. In commercial d-c generators, a group of conductors, mounted on an armature, rotate in a fixed magnetic field.

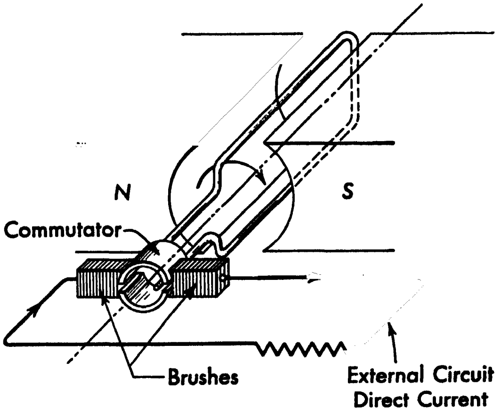


FIG. 101 Elementary d-c generator. (*Copyright 1946 National Carbon Company, Inc.*)

The value of the electromotive force induced in a single conductor as it passes through a magnetic field is directly proportional to the effective length of that conductor, the strength of the magnetic field, and the speed with which the conductor moves through that field. From this relationship it is possible to set up the fundamental equation of the generator, which is generally stated as

$$E \text{ (volts)} = \phi S K$$

where

E is the electromotive force (volts).
ϕ is the magnetic flux which enters the armature at each north pole.
S is the speed of the conductor moving through the magnetic field.
K is a constant for the machine, depending for its value on the number of armature conductors, the number of paths in the armature, the number of field poles, etc.

This equation is given to bring out the fact that the voltage output of a given d-c generator can be varied either by changing the speed of the armature or the strength of the magnetic field.

When the field strength is fixed, the output of the generator will be in direct proportion to its driven speed. The tachometer generator, used to measure speed, is an example of the fixed field generator. This generator is provided with a fixed field, often a permanent magnet, and is directly connected to the machine whose speed is to be measured. The terminals of the generator are connected to a voltmeter calibrated to read in revolutions rather than in volts. By this arrangement, the speed of the machine can be read on the scale of the meter. The tachometer generator is an important unit in certain variable-voltage speed-control systems, where it is used to give a signal when the speed deviates from the normal.

The output of a constant-speed d-c generator is controlled by varying the magnetic field strength. This method is commonly used in most commercial d-c generators, as they are usually driven at a fixed speed. It is the method most often used to obtain the desired voltage in speed-control systems.

The generator field windings may be connected either in series or in parallel with the armature circuit just as they were in the motor. The series-wound generator, however, is now rarely used. Most modern d-c generators are either shunt or compound wound. Armature windings are also similar to those used in motors and the same types and variations are common to both machines The discussion previously given for both motor field and armature windings also applies to generator windings

When a generator is first started, no current is flowing in the field coils (assuming that the field is not separately excited) and the voltage generated depends on the residual magnetism in the field pole pieces As generation begins part of the voltage is impressed on the field causing an increase in field strength This increased field strength causes a further increase in the voltage generated This process continues until rated voltage is reached and is known as the *building up* of the field This takes an appreciable time, often a minute or more, depending on the size and construction of the particular machine

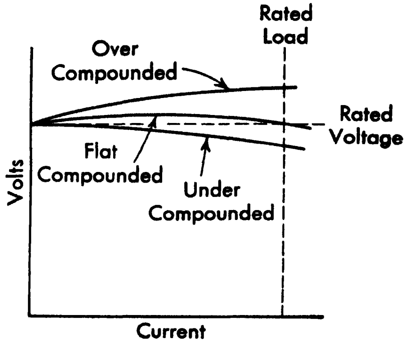


FIG 102 Characteristic curves of compound wound generators

When a generator has built up, the output voltage can be controlled by means of a rheostat in the field circuit This is necessary when the load on the generator fluctuates widely The actual amount of the voltage variation due to change in load depends on the type of the generator winding Figure 102 shows the characteristic curves of three types of compound-wound generators When the series- and shunt-field windings are so proportioned that the voltage increases with an increase in load, the generator is said to be overcompounded When the voltage gradually falls with the increased load, the machine is said to be undercompounded In the case of the flat-compound generator, the terminal voltage first rises slightly and then falls so that the no-load voltage is approximately the same as the full-load voltage

Commercial machines for power generator are usually wound so as to be slightly overcompounded The amount of compounding can be readily changed by use of a low-resistance shunt around the series field coil The position of this shunt resistor is shown in Fig 103 Changing the value of this shunting resistor will change the droop of the characteristic curve of the machine. It is sometimes necessary to do this in order to operate generators in parallel.

The drop in voltage with increase in load is more pronounced in the simple-shunt generator. If such a generator is designed to give rated voltage at full load, then, when the load is removed, this voltage will rise. Because of this characteristic, the shunt-wound generator is not well-suited to applications where constant terminal voltage is an essential requirement.

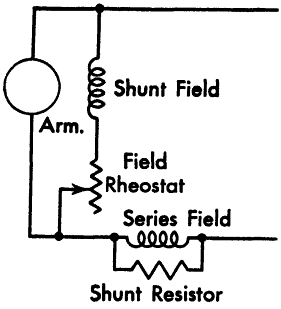


FIG. 103 Connection diagram of shunt resistor used to change the droop of the characteristic curve.

Generators used in connection with variable-voltage speed-control systems are usually separately excited. The desired output voltage is obtained by precise control of the field. These generators often have several independent windings on their field poles. Frequently one set of windings will be arranged to oppose the remaining field windings. By controlling the current in the opposing circuits, the voltage output of the machine can be varied over an extremely wide range.

The phenomena of armature reaction discussed in Chap. 7 applies to generators as well as to motors. Armature reaction has the general effect of decreasing the terminal voltage as the current in the armature windings increases and shifts the neutral plane from the geometric neutral to a position slightly forward in the direction of rotation. This is illustrated in Fig. 104. It should be noted that this is the exact opposite of the shift of the motor's neutral plane. To restore the commutating plane to the geometric neutral, interpoles are used just as they are in motors. In the case of the generator, however, the polarity of the interpole is the same as that of the next adjacent main field pole moving forward in the direction of rotation. As with the motor, the use of interpoles greatly improves commutation but does not prevent field distortion. To reduce field distortion, compensating windings are used. These windings are set into the face of the main field poles. Figure 105 shows the frame of an engine-driven d-c generator with the compensating windings shown across the face of the main poles. These windings are made in the form of heavy copper ribbons and, being in series with the armature, carry the full-load current of the generator. The small poles seen between the main field poles are the interpoles.

The general construction and types of enclosure of the generator are similar to those described for motors. The bearings, commutator, brush rigging, and brushes all follow the same pattern as those previously described. The suggestions for maintenance, as well as the trouble charts and testing methods already given, are also applicable to generators. There is, however, one difficulty unique to generators. This is the possible failure of the generator to build up when placed into service.

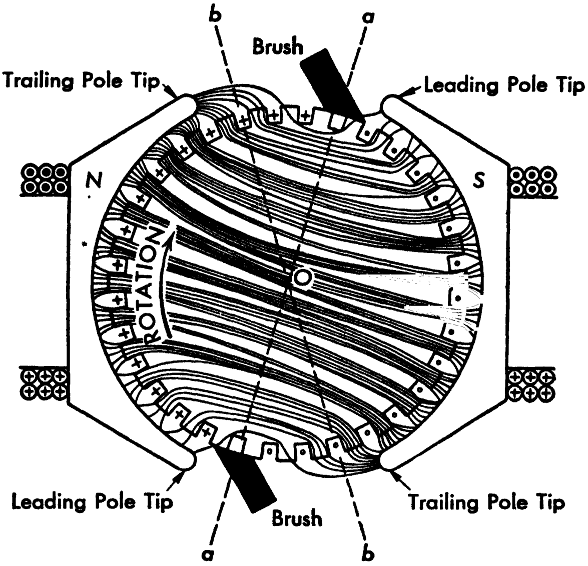


FIG. 104 Shifting of the geometric neutral in a generator. (Compare with Fig. 28 for the shifting of the neutral plane in a motor.) (*Copyright 1946 National Carbon Company, Inc.*)

The most common cause of the failure of a generator to build up is the loss of its residual magnetism. Normally, the frame and pole pieces possess sufficient magnetism to enable the generator to start the building-up process. A machine which has been idle for some time may lose its residual magnetism. Magnetic flux or stray currents from adjacent equipment may weaken or completely neutralize the residual magnetism. Excessive vibration of an idle generator is another cause of this magnetic loss.

To restore the residual magnetism, it is necessary to excite the field from another source of voltage Often a group of dry cells or a storage battery is all that is needed. The usual method, in the case of a compound-wound generator, is to separate the shunt and series field windings, after which the battery is connected to the series winding while the shunt winding is connected across the armature circuit. Care must be exercised in making these connections to have the current flowing in the proper direction. The battery current in the series windings will set up sufficient magnetic flux to enable the generator to start building up.

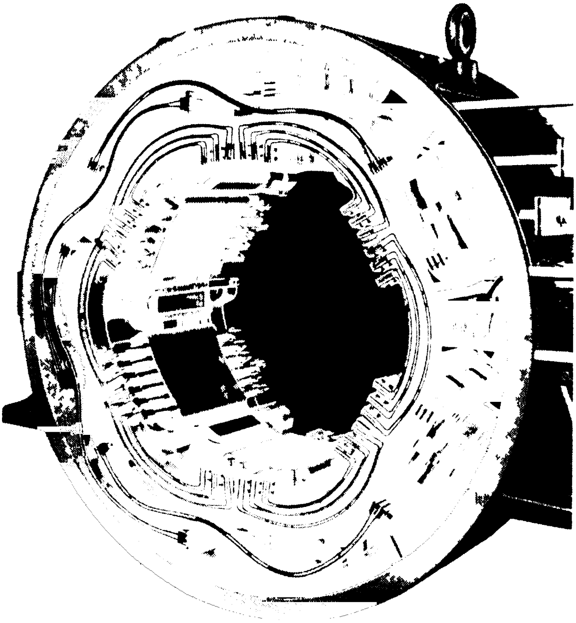


FIG. 105 Field frame of an engine driven d-c generator The compensating windings seen across the main field poles are similar to those used on large d-c motors (*Burke Electric Co.*)

A generator whose shunt field winding has become open-circuited will fail to build up. The open circuit may be due to a break in the field winding or to an open circuit in the field rheostat. Testing the complete field-winding circuit for continuity with the generator idle will usually reveal this condition. The field circuit should be completely isolated from all other circuits when this test is made.

Reversal of the residual magnetism may cause the generator to build up in the wrong direction. This condition is often the result of an external source of power flowing through the field winding in the wrong direction. This can be detected by use of the pocket-compass test as described for testing motor field poles. The correction can be made by use of a battery, as previously described.

Other causes of the failure of a generator to build up are: too much field-rheostat resistance in the shunt-field circuit; poor contact at the brushes due to a dirty commutator; incorrect setting of the brush position; and, finally, a broken connection either in the machine itself or in the field rheostat.

Special types of generators which have no counterpart in motors are often used for certain particular applications. One of these is the three-wire generator, a machine designed to supply a three-wire distribution system with two voltages, 115 volts and 230 volts, for example. The welding generator is another special-type machine. This generator is designed to have a high terminal voltage on open circuit so that the welder may strike his arc. Once the arc is struck, the voltage immediately drops and the machine generates a high current at low voltage which is necessary for successful welding. Three brush generators are widely used in automotive service so that the output voltage will not fluctuate with wide variations of engine speed. These special generators are of little importance to motor users. Those that do concern motor users are discussed in greater detail in the chapters which follow.

CHAPTER 25 Variable Voltage Speed Control

It was pointed out in Chap. 23 that speed control of a d-c motor may be obtained by varying the impressed electromotive force on the armature while the field circuit is held constant. To accomplish this without the use of resistors requires a source of variable voltage. Since commercial power systems supply only constant voltage, a local source of variable voltage must be provided. This necessitates the installation of a motor-generator set. There are many sound economic reasons for so doing. For one thing, it permits the use of direct current motors where the only available power supply is alternating current. The availability of a direct current power supply is rather limited. The superior speed-torque characteristics and speed regulation of the d-c motor over the a-c motor often in itself justifies the use of a motor generator set between the source of supply and the driving motor. With a variable-voltage supply, the use of regulating resistors, relays, and contacts is almost completely eliminated, resulting in a comparatively simple and more efficient speed-control system.

The basic system of variable-voltage speed control was developed some years ago by Ward Leonard and is usually referred to as the *Ward Leonard control system*. While a few industries have used the Ward Leonard system for some time, it is only comparatively recently that it has come into widespread use. This is because of the need of very precise and accurate speed control in many modern industrial processes.

A schematic representation of the fundamental Ward Leonard control circuit is shown in Fig. 106. An alternating-current motor, a direct-current generator, and an auxiliary direct-current exciter generator are mounted on a common base and are all directly connected by a common shaft. This unit is the essential motor-generator set of the Ward Leonard system. The exciter unit supplies a constant voltage for the field supply of both the d-c generator and the d-c motor which is being controlled. This constant-voltage supply is shown in the schematic circuit as the exciter bus. The armature circuit of the d-c generator is directly connected (usually without control devices) to the armature circuit of the d-c motor. This circuit is called the power loop

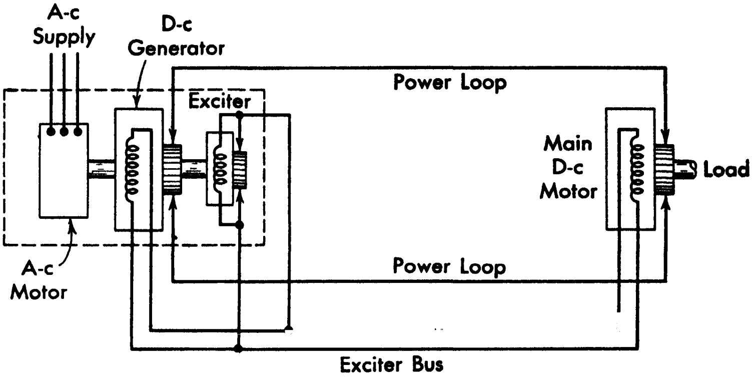


FIG. 106 Schematic representation of the Ward Leonard control circuit.

and remains closed at all times during normal operation. The voltage output of the d-c generator is controlled by means of a field rheostat which is inserted in the generator field circuit between the generator and the exciter bus. This gives very accurate control of the voltage in the power loop. Since the current in the field circuit is comparatively small, a rheostat wound with fine wire and a large number of steps can be used. A small adjustment of this field rheostat will produce a considerable variation of the power-loop voltage. It may therefore be thought of as acting somewhat in the manner of an amplifier. In some instances, the motor is also provided with a field rheostat to obtain speeds above normal. The exciter unit is frequently provided with a field rheostat and voltage regulator for the purpose of maintaining the proper constant voltage on the exciter bus. The all important controlling rheostat, however, is the one used in the field circuit of the d-c generator. With the d-c motor field held at constant voltage, full torque will be developed by the driving motor over a wide range of speed by simply adjusting the generator field rheostat.

The starting and stopping of the driving motor is controlled entirely by the output voltage of the d-c generator without the use of control devices in the power loop. Reversal of the driven motor is accomplished by reversing the current flow in the generator field, which causes a reversal of the direction of flow in the power loop. For this purpose, a double-pole double-throw reversing switch is installed in the d-c generator field circuit. It is important to note that practically the entire control of the driven motor is accomplished by simple adjustment of the d-c generator field circuit. When it is desired to stop the motor, it is necessary to stop the current flow in the power loop. It often happens that, due to the residual magnetism in the d-c generator frame, this generator will continue to put out a low voltage even after the field circuit has been opened. This low voltage in the power loop may cause the motor to creep and not come to a full stop. To completely kill the output of the d-c generator, it is necessary to feed part of this low voltage in the power loop back through the generator in a reverse

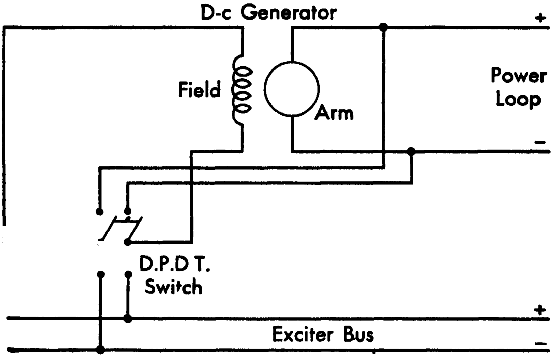


FIG. 107 Choking circuit for use with the Ward Leonard contiol system.

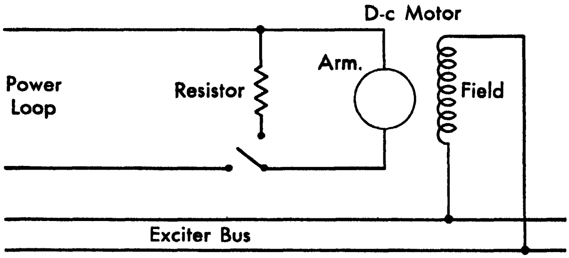
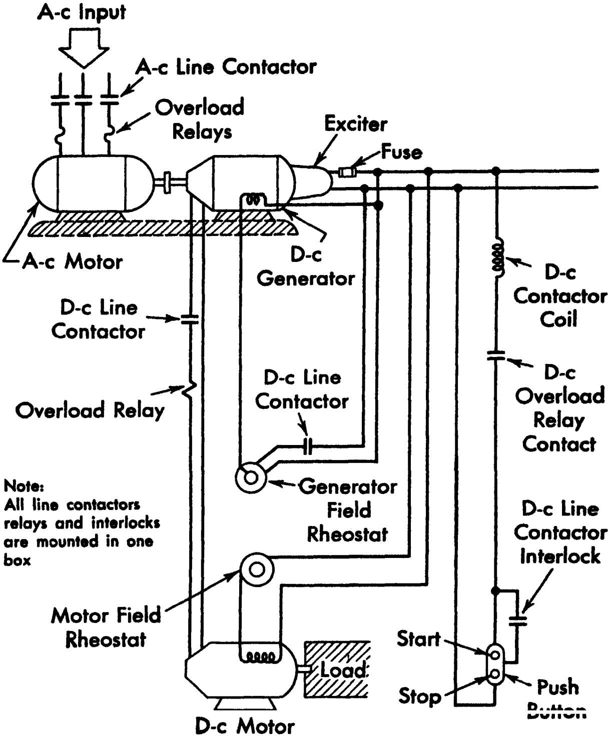


FIG. 108 Dynamic braking circuit for use with the Ward Leonard control system.

direction. This effectively chokes off the generator output and brings the motor to a stop. Connections for accomplishing this are shown in Fig. 107. Note particularly that the double-pole double-throw switch changes the direction of the current in the field coils when transferring the field from the exciter bus to the power loop. This switch should not be thrown until the speed of the motor has dropped to a low value; otherwise, due to the momentum of the motor, it may act as a generator and cause a heavy circulating current to flow back in the loop circuit. The switch must be returned to its normal position before attempting to start the motor again.



Note:
All line contactors relays and interlocks are mounted in one box

FIG. 109 Stylized connection diagram of the speed-variator circuit. (*General Electric Company*)

When it is desired to stop the main motor .quickly, some form of dynamic braking may be used. This requires the opening of the power-loop circuit and the insertion of a block of resistance in the motor-armature circuit. Full field current is maintained on the motor at all times. Figure 108 shows the main driving motor only and a portion of the power loop with the connections for dynamic braking. A single-pole double-throw switch will transfer the motor armature from the power loop to the dynamic braking resistor. It should be noted that while simple manual switches have been shown in the circuits of the Ward Leonard system, magnetic contactors are generally used. Many of the braking circuits discussed previously can be modified for use with the main motor of the Ward Leonard system.

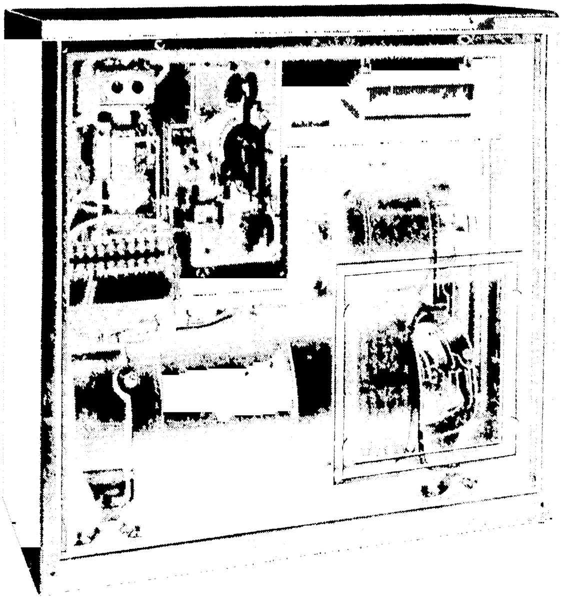


FIG. 110 Phantom view of Reliance V★S adjustable speed control unit (*Reliance Electric & Engineering Co.*)

The Ward Leonard system of speed control appears on the commercial market under various trade names. The General Electric Company, for example, offers its *speed variator* as a "packaged, all electric drive, including driving motor, motor generator set and control." The stylized connection diagram of the speed-variator circuit is shown in Fig. 109.

It is interesting to compare this circuit with the basic Ward Leonard connections. The d-c generator includes an exciter unit which is mounted on its frame. The speed variator is offered as a complete unit in ratings from 1 horsepower and larger with speed ranges of 8, 12, and 16 to 1. The d-c driving motor can be started and stopped in most cases by the push-button control without disturbing the speed setting of the rheostat. There is a line contactor in the power loop as well as in the d-c generator field circuit. Other manufacturers offer similar packaged drives.

Since complete control over the driving motor in the Ward Leonard system is obtained by the simple movement of a single rheostat, remote control of speed is feasible by using a motor driven rheostat. By this means, an operator at a distant point has complete control over the speed of the motor at all times.

The Ward Leonard system is also suited for drives where several motors are operated in parallel and must be held at constant speed at all times. One motor generator set of suitable capacity will operate all such motors at the same speed after the initial adjustments have been made. Certain industries, steel-rolling mills, textile making, and paper manufacturing, to name a few, require a number of motors to operate at identical speeds. The Ward Leonard system, with modifications, finds extensive use in such industries.

The fact that a single-field rheostat can control the speed of the driving motor has led to the development of a number of systems of closed-cycle control. The term *closed cycle* is applied to control systems which are self-regulatory. When such a system is applied to speed control, a standard speed is determined and any deviations from the standard are automatically corrected. One way of accomplishing this is by use of a tachometer generator directly connected to the driving motor. The output of the tachometer is so connected that should the speed either rise or fall slightly below the standard, it will function to actuate a motor-driven field rheostat on the d-c generator in such a way that the voltage in the power-loop circuit will change in a corresponding manner to restore the motor to its normal speed. It should be noted that in this arrangement, the speed must deviate a certain amount from the standard before the tachometer will set the rheostat in motion. Then again, once the rheostat is started, an appreciable time is required for the rheostat to move to make the necessary correction. Furthermore, in such a control system, there will be a tendency to *hunt*: that is, too much correction will be applied before the tachometer can act to stop it, causing it to overshoot. This will cause the tachometer

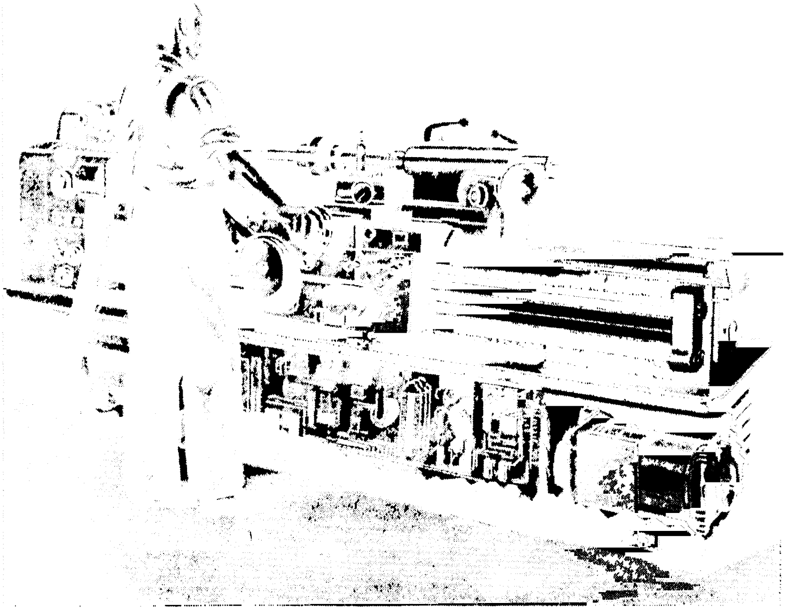


FIG. 111 Machine tool application of variable speed drive. Cutaway section in base shows (*left to right*) d-c adjustable speed drive motor, control panel, and power unit. (*Reliance Electric & Engineering Co.*)

to apply a correction in the opposite direction. The net effect of this is to cause the control system to oscillate. The constant swinging back and forth defeats the very purpose for which the speed-control system was intended. With the need of some system of automatic or closed cycle control, the attention of design engineers was directed to the fundamentals of the Ward Leonard system. It was realized that if the generator field rheostat could be eliminated in favor of controlling the output of the *exciter*, the problem could be solved. This has led to the development of the *exciter regulator*, which is now having wide acceptance in modern speed-control installations.

CHAPTER 26 Regulating Exciters

Regulating exciters are conventional d-c generators specially designed to make their output voltage vary in direct proportion with changes in their field current. They appear to have almost unlimited application in a wide variety of systems for the control of voltage, torque, speed, current, and power factor. The discussion here will be limited to their application in connection with d-c motor speed control.

One popular form of regulating exciter is the *rototrol* of the Westinghouse Electric Corporation. The word *rototrol* is their trade name, formed by combining the first and last syllables of the words "rotating control." This exciter differs from the standard d-c generator in its field windings. It is provided with a number of independent field windings which are connected to the external electric circuit in various ways, depending on the regulating problem. These windings are superimposed on the conventional field poles. For speed regulating, the Rototrol is usually provided with either three or four field windings. These windings are electrically separate but are physically wound as

FIG. 112 Typical Rototrol unit with driving motor enclosed in single frame. (*Westinghouse Electric Corp.*)

a unit on the pole pieces. Except for the number of leads from the field windings, the Rototrol has the appearance of the standard d-c generator. A typical unit with the driving motor in the same enclosure is shown in Fig. 112.

The basic diagram of the three-field Rototrol is shown in Fig. 113. The self-energized field is usually connected in series with the armature. This field supplies the main excitation of the generator. The remaining two fields are used merely to modify this main exciting field. One of these fields is connected to a supply of constant voltage and is designated as the *control field*; the other field is connected to a small tachometer generator attached directly to the shaft of the main drive motor and is known as the *speed field.* If the control field and the speed field are so adjusted as to cancel each other during normal operation, the output of the Rototrol will be due solely to the flux set up by the self-energized field. Connections are made to cause the current to flow in each coil as shown by the direction of the arrows in Fig. 113. By use of adjusting resistors (not shown in the diagram) the two fields can be made to exactly cancel each other when the driven motor runs at normal speed. Should the speed of the driven motor change, there will then be a change in the output of the tachometer generator on its shaft. This will cause the balance between the control field and the speed field to be upset and the new resultant field will exert a corrective action on the output of the Rototrol. This will tend to restore the speed of the driven motor to normal and thus again bring the two fields in balance. Should it be desired to vary the speed of the driven

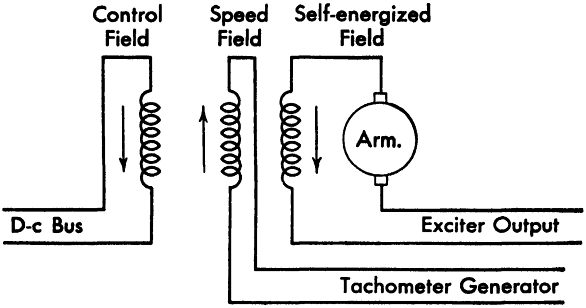


FIG. 113 Basic diagram of the three-field Rototrol. (*Westinghouse Electric Corp.*)

motor at any time, the voltage of the control field can be changed by inserting a rheostat in the circuit between the control field and the constant d-c voltage bus.

The complete elementary diagram for speed regulation using a tachometer generator as a measure of speed and a three-field Rototrol

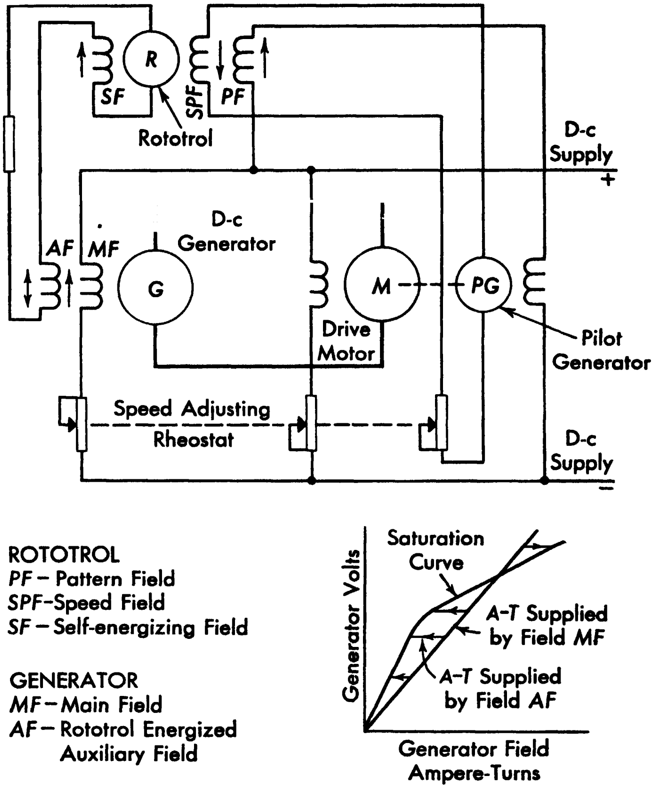


FIG. 114 Elementary diagram for speed regulation with a three-field Rototrol. (*Westinghouse Electric Corp.*)

regulating exciter is shown in Fig. 114. The generator *G* is driven by an a-c motor not shown in the diagram. If there is no source of power available for the d-c supply, then another d-c generator in addition to the equipment shown in Fig. 114 must be provided for. The regulating exciter output is connected to an auxiliary field on the main generator and supplies the necessary correction for speed regulation. The main field of the d-c generator is supplied from the d-c bus. This arrangement is merely a modification of the basic Ward Leonard control system. Any speed deviation of the main motor changes the output of the small tachometer generator (shown as *PG* in Fig. 114) which feeds the Rototrol speed field. This change upsets the relation between the speed field and the control field (shown as *PF* in Fig. 114). The series connection between the tachometer generator field and the Rototrol control field compensates for changes in control voltage and field coil temperature. In this system, the tachometer generator serves as a measure of the main drive motor's speed.

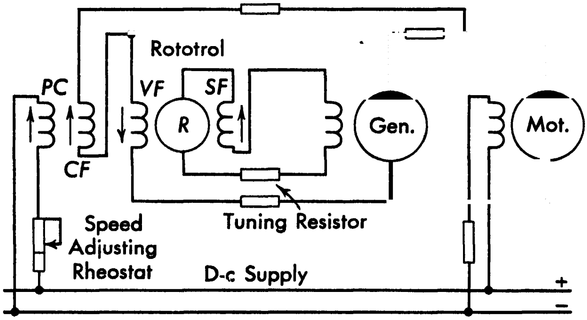


FIG. 115 Counter electromotive force speed control circuit with a four field Rototrol. (*Westinghouse Electric Corp.*)

Another system of speed control with the Rototrol regulating exciter is based on a measure of the counter electromotive force of the motor. Its purpose is to hold the speed constant regardless of changes in the load on the motor. It is based on the fact that the speed of a d-c motor with constant-field excitation is directly proportional to the counter electromotive force of the motor. A change in the counter electromotive force of a motor causes a corresponding change in the current in its armature circuit. Figure 115 shows the general arrangement for speed control by the counter electromotive force method. A Rototrol exciter with four fields is used. In addition to the basic self-excited field, there is a control field (as already described), a current field, and a voltage field. These last two mentioned fields serve as a measure of the current and the voltage in the power loop circuit. A study of the connections shown in Fig. 115 should make this clear. The arrows adjacent to the various fields indicate the normal direction of the current flow in each. It should be understood, of course, that all the fields must be properly adjusted and balanced at the time the original installation is made. For this purpose *tuning resistors* (shown by rectangles in Fig. 115) are usually inserted in the various field circuits. Speed adjustment, when desired, is obtained by means of a rheostat in the Rototrol control field circuit.

The Rototrol exciter is also widely used where the application requires maintaining constant torque rather than constant speed. In paper manufacturing, textile weaving, steel strip mills, and similar industries where the finished material is reeled on drums or spools, the speed of the motor must gradually change to compensate for the change in the size of the reel. Here the controlling factor is the torque of the motor as the tension on the material must be kept uniform. Since the torque of a d-c motor is directly proportional to its armature current (assuming constant field strength), the current in the power loop can be taken as a measure of the motor's torque. By using connections similar to Fig. 115, but without the voltage field, the Rototrol can be used to maintain constant current in the power loop and thus control the torque of the motor.

A somewhat different form of regulating exciter is made by the General Electric Company under the trade name of *Amplidyne*. This name was derived from the words amplify and dynamo. Because a comparatively large output can be controlled by a very slight change in the amount of the input, this machine may be regarded as a form of amplifier. To properly understand how this is accomplished, it is necessary to review certain fundamentals of the conventional d-c generator.

Figure 116 is a schematic representation of a d-c generator, with the armature serving also as the commutator for the sake of simplicity. The field coil which produces the excitation is represented in cross section as being wound around the north pole only. Suppose such a generator has a rated output of 10,000 watts (100 amperes at 100 volts). Then about 100 watts excitation power supplied to the field will produce the full-load voltage of 100 volts which circulates the full-load current of 100 amperes through an assumed load of 1 ohm. This load current of 100 amperes flows through the armature conductors and creates an armature flux. This is indicated by the loop marked armature flux in Fig. 116. This armature flux is of very nearly the same magnitude as the original excitation flux (also marked in Fig. 116), but it is not doing any *useful* work. It should be noted that the excitation flux and the armature flux are at right angles to each other.

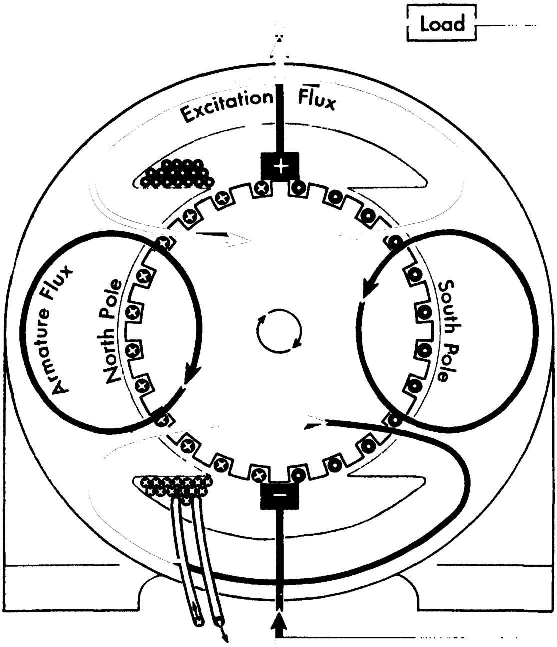


FIG. **116** Armature flux and Excitation flux in a d-c generator. (*General Electric Company*)

Figure 117 shows the same generator as the previous figure, but with a greatly reduced field winding and the excitation power reduced from 100 watts to 1 watt. This is because the number of turns on the field coil has been reduced from 100 to 1. This new reduced excitation power creates only 1 per cent of the original excitation flux. Voltage at the brushes is now reduced from the original 100 volts to 1 volt, and the load current is reduced from 100 amperes to 1 ampere with the same 1 ohm load. This, of course, reduces the armature flux to 1 per cent of its previous value. It is obvious that the full-load working flux has been sacrificed by the reduction of the field-excitation power.

Now suppose that we reduce the external load from 1 ohm to 1/100 ohm. This can be accomplished by disconnecting the external load entirely and short-circuiting the brushes, assuming that the internal resistance of the armature winding is but 1/100 of the original external-load circuit. This immediately causes a rush of current to flow in the armature conductors which, in turn, restores the armature flux to its original value. This is indicated in Fig. 118. It is important to note that by short-circuiting the brushes, the field-excitation power and flux continue to be very small, but they now control a full-size armature flux. This full-size armature flux is still idle and is not doing any useful work.

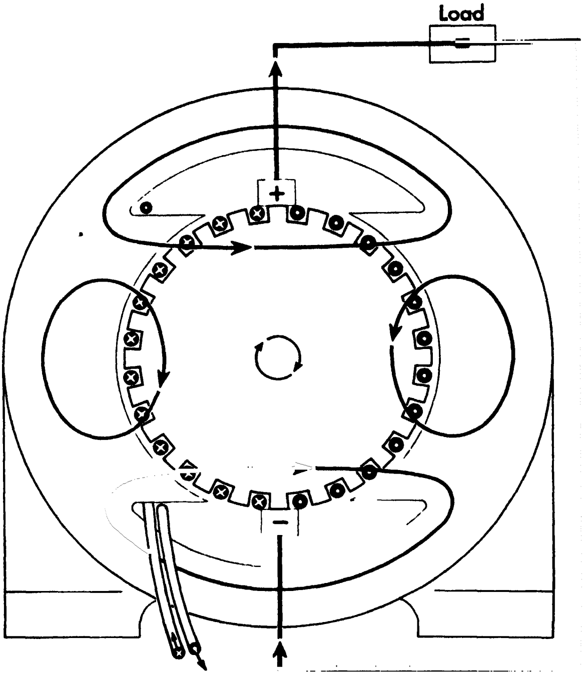


FIG. 117 The effect of reducing the field winding. Note the greatly reduced size of the load as compared with Fig. 116. (*General Electric Company*)

Since the full-armature flux is at right angles to the original field-excitation flux, suppose a new set of brushes is added at right angles to the original short-circuited brushes. The armature flux is full size and so produces 100 volts (the original voltage) between the new brushes. These new brushes are now connected to the external load, one directly and the other through a compensating field shown at the right in Fig. 119. In the same armature conductors, the new load current adds to and subtracts from the short-circuited armature current. The function of the new compensating field winding is to neutralize any tendency of the load current to set up its own armature flux in opposition to the control flux. A single watt of power in the original field winding will control an output of 10,000 watts, a ratio of 1 to 10,000. This is the basic Amplidyne generator.

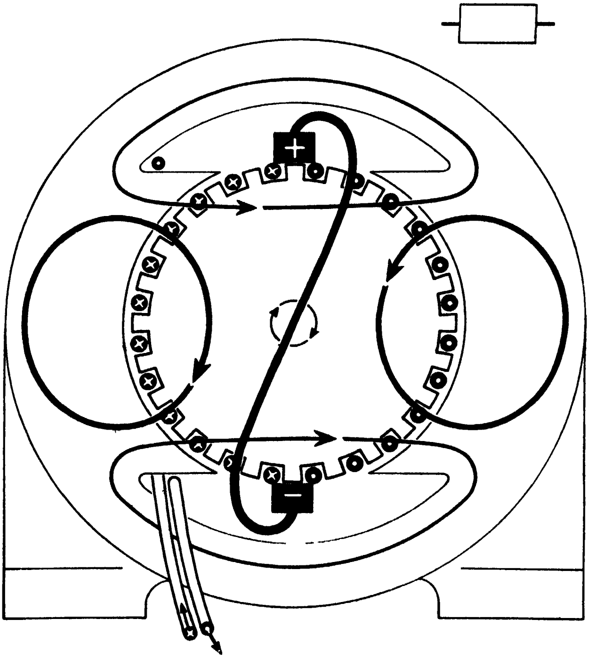


FIG. 118 The external load is disconnected and the brushes are short-circuited. (*General Electric Company*)

The Amplidyne just described is provided with a single control field winding. However, if several control field windings, independently excited by signal devices, are placed on the same pole structure, the Amplidyne will respond to their resultant action and amplify the output in the same manner as with a single field.

The enormous amplification power of the Amplidyne makes it ideally suited for use with electronic devices where a weak signal output can be fed into the control field of the Amplidyne to produce a very high response. It has the further advantage of responding to the control signal almost instantaneously. It is, therefore, an ideal regulator where any type of precise control is required. It has many industrial uses in addition to those of speed control applications which are discussed here. Some of these are voltage control, current control, power control by positioning, positioning in motion, and power-factor control.

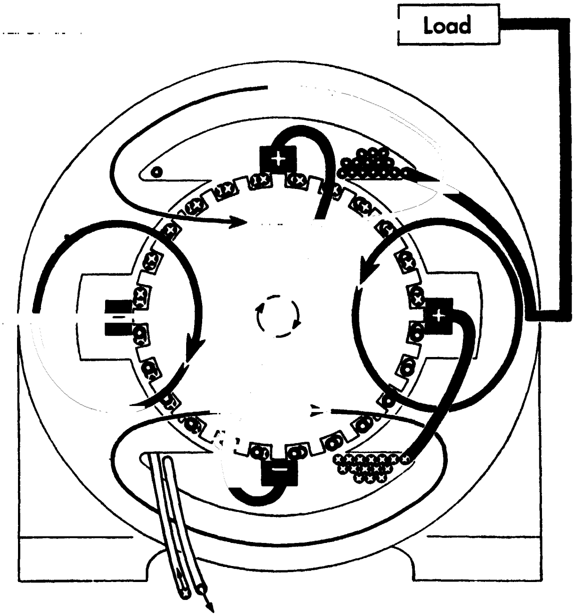


FIG. 119 The basic Amplidyne generator. (*General Electric Company*)

Speed-control circuits using the Amplidyne resemble those given for the Rototrol. Figure 120 shows the tachometer-type speed-control circuit which should be compared with the circuit given in Fig. 114. In this curcuit, instead of feeding the entire output of the tachometer into the control field, only a portion of it is used. This is the voltage drop across a resistor in the tachometer output circuit. This is sufficient to produce the desired output because of the high-amplification power of the Amplidyne.

The Rototrol and Amplidyne are but two forms of regulating exciters. There are a number of others available, all of which more or less follow the same fundamental pattern. Most depend on the use of multiple-field circuits, so arranged and so balanced, that a small signal derived from a variation in the performance of the drive motor will effect the necessary correction.

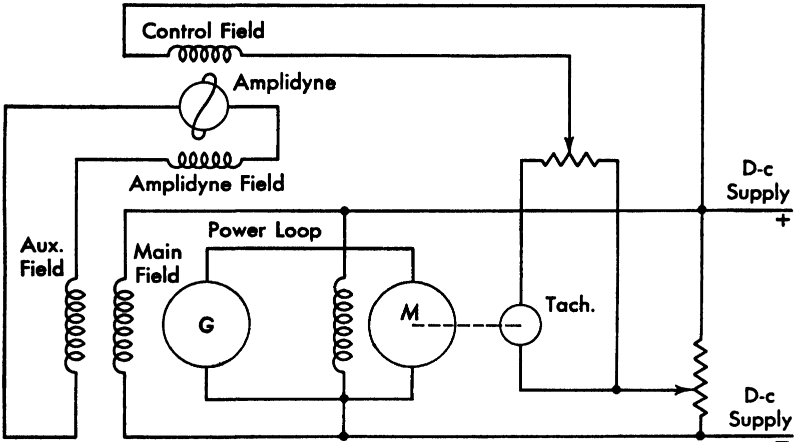


FIG. 120 Typical Amplidyne speed control circuit.

A special form of speed control for cranes and hoists has been developed by the General Electric Company under the trade name of *maxspeed system.* In this system the closed Ward Leonard power loop is fed back through a special field winding on a machine known as a *cross flux* exciter. This cross flux exciter supplies current to the generator field and at the same time modifies the excitation of the drive motor field. This can be seen in the elementary diagram shown in Fig. 121. The purpose of this system is to pay out light line quickly and yet reduce the speed of a heavy overhauling load. This is an especially desirable characteristic in crane and hoist applications. In the cross flux exciter, each pole piece is provided with a shunt winding excited from the constant-voltage excitation bus and a cross field winding consisting of a few turns of heavy conductor connected in series with the power loop circuit. The design is such that at zero current in the loop circuit, the voltage output of the exciter is at its maximum, and as the current flow in the loop circuit increases, the voltage of the exciter decreases. By means of this arrangement the desired result of paying out light line faster than loaded line is accomplished.

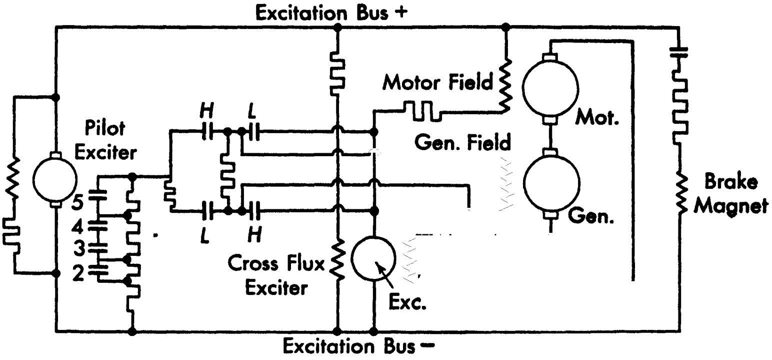


FIG. 121 The Maxspeed system of control. (*General Electric Company*)

The greater the sensitivity of any closed cycle control system, the more likely it is to *hunt*. Special circuits have therefore been developed for the purpose of slowing down the *rate of change* in the output of the regulating device and yet only slightly decrease the speed with which stabilization is obtained. Most of these schemes require the use of an additional field known as the anti-hunt field. This anti-hunt field is connected to some auxiliary device whose current output is proportional to the rate of change of the signal in the control circuit rather than the magnitude of the control signal. The general effect of the anti-hunt field is therefore to oppose extremely rapid changes in the control circuit. These anti-hunt circuits differ with the particular application at hand and are subject to so many variations that it is impossible to give a detailed discussion of all of them here. One typical anti-hunt circuit is shown in Fig. 122. Here the primary winding of a special anti-hunt transformer is connected across the output of the Amplidyne. Since this output is direct current, as long as it remains constant, no voltage is induced in the transformer secondary winding and hence no current flows in the anti-hunt field. When the Amplidyne output changes, a voltage is then induced in the transformer secondary winding which is proportional to the rate of change in the Amplidyne output. As a result, a proportional current flows in the anti-hunt field which opposes too rapid a change in the Amplidyne output voltage. In this way, the output is stabilized and hunting reduced to a minimum. In a variation of the circuit shown in Fig. 122, the primary of the anti-hunt transformer is connected across the terminals of the tachometer in the circuit of Fig. 120, thus making the current in the anti-hunt field proportional to the rate of change in the tachometer output. This would have a similar stabilizing effect.

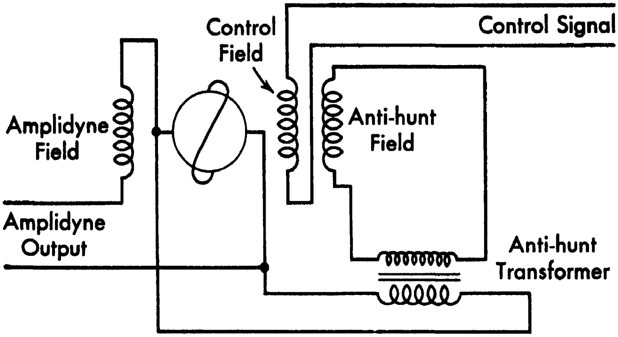


FIG. 122 Typical anti-hunt circuit with an Amplidyne control system.

CHAPTER 27 Electronic Rectifiers

THE introduction of electronic devices has probably had a great deal to do with the increased use of the d-c motor in industry. There is ample reason to believe that the use of electronic devices in industry is in its infancy and that the future will see a constantly increasing application of such devices. For this reason, it is felt that a discussion of this subject should be included in a manual of direct-current motors.

Electronic equipment has two basic applications in connection with the operation of the d-c motor. In the first instance, as rectifiers to enable the d-c motor to operate from an a-c power supply, and in the second instance, as regulating or relay devices to control the performance of the d-c motor more accurately and more efficiently than hitherto believed possible. The first of these basic applications will be discussed in this chapter.

The electronic principles which are to be discussed here pertain to those in connection with d-c motor application; it is assumed that the elementary electron theory of the flow of an electric current in a vacuum or gas-filled enclosure is understood. These enclosures are popularly called *tubes* and may be either glass or metal or a combination of both.

All electronic tubes are basically rectifiers, that is to say, they permit the flow of current to pass through them in one direction only. Some types of industrial electronic tubes are used exclusively as rectifiers, while in others, the rectifying action is merely incidental to their main function, which is to *control* the current flow. In general, within the tube itself, the current flows only from the *cathode* to the *anode*. The cathode is the source from which the electrons are emitted, while the anode is the plate towards which they move. In order to attract electrons, the polarity of the plate (anode) must be positive as compared with that of the cathode. This is because the electrons themselves are negative charges. When the anode is negative with respect to the cathode, it no longer attracts electrons, but tends to repel them. The amount of current which can flow through an electronic tube is limited primarily by the capability of the cathode of giving off electrons. The electrons which the cathode emits carry the current towards the anode. Between the cathode and the anode, there may or may not be other elements whose function is to control the electron flow. Usually these are known as *grids*.

Industrial electronic tubes may be divided into two broad general classes—vacuum tubes and gas-filled tubes. Neither term is to be taken too literally. The word *vacuum*, as used here, refers to as high a vacuum as is commercially possible. Gas-filled tubes usually contain only a small amount of gas at very low pressure. Actually, the tube is far from being completely filled, as the name might imply. In fact the very word *gas* is misleading, as mercury vapor is used in many instances. High-vacuum tubes are capable of handling only a small fraction of an ampere of current at comparatively high voltages, whereas the gas-filled tube will pass a considerable quantity of current. Vacuum tubes, when supplied with grid elements, are used for control purposes because the grid element can be made to start, stop, or regulate the flow of electrons within the tube. Gas-filled tubes can only start the flow of current within itself. They are not able to stop the flow of current once it has started, nor can they control the magnitude of the current as does the high-vacuum tube. In general, gas-filled tubes are essentially power devices, while vacuum tubes are control devices.

Most commonly used to change alternating current into a source of direct current is the mercury-arc rectifier in the form of an electronic tube known as the *ignitron*. In the ignitron, the cathode is a pool of mercury which provides an almost unlimited number of electrons to carry the load. The anode is a comparatively large block of graphite, this material being chosen as it does not emit electrons under normal operating conditions. To start the flow of electrons from the surface of the mercury pool, a starting electrode called the *ignitor* is used. This electrode causes a small spark to form on the surface of the mercury. This spark quickly spreads over the entire surface of the mercury pool and starts the flow of billions of electrons which carry the required current from the cathode to the anode. This ignitor is a tapered piece of boron carbide which extends down into the mercury pool, but is not made wet by it. Once the ignitor starts the flow of electrons, the anode will attract them as long as the voltage applied to it is positive. When an ignitron is connected to an alternating-current supply, the anode is

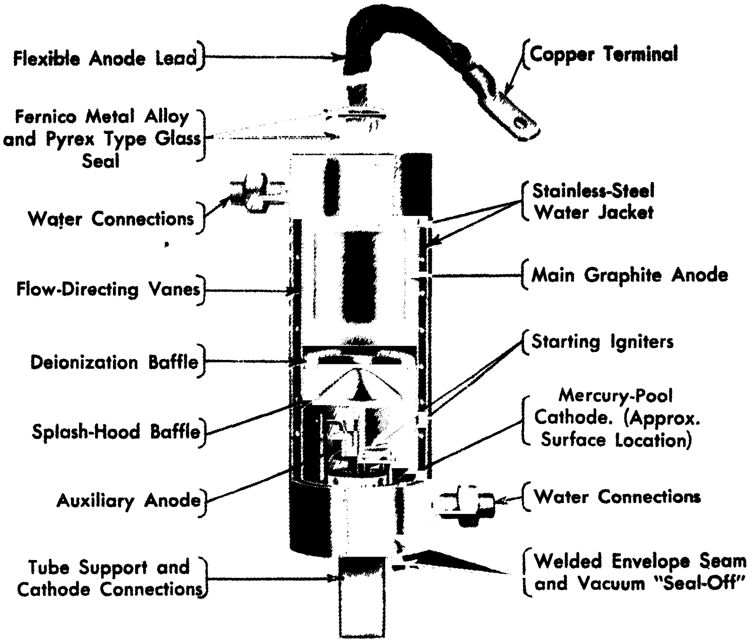

Flexible Anode Lead
Copper Terminal
Fernico Metal Alloy and Pyrex Type Glass Seal
Water Connections
Stainless-Steel Water Jacket
Main Graphite Anode
Flow-Directing Vanes
Starting Igniters
Deionization Baffle
Mercury-Pool Cathode. (Approx. Surface Location)
Splash-Hood Baffle
Auxiliary Anode
Water Connections
Tube Support and Cathode Connections
Welded Envelope Seam and Vacuum "Seal-Off"

FIG. 123 Cross section of a typical Ignitron. (*General Electric Company*)

positive during one-half of each a-c cycle. During the other half of the cycle, the anode is negative and will no longer attract electrons. As a result, the current flow will stop. When the anode again becomes positive during the next alternating-current cycle, the ignitor must again cause a spark and re-establish the current flow. Thus the ignitron allows the current to flow in one direction only and becomes a source of direct current. It should be pointed out that the ignitor ceases to function once the current flow has started. It is therefore necessary to have an entirely separate circuit to energize the ignitor at the proper instant in order to re-establish the current flow. This is generally known as the *excitation circuit.* If but a single ignitron tube is used, the resulting output would actually be pulsating direct current. When a 60-cycle a-c supply is used, current flows for 1/120 second and then stops for 1/120 second because of the reversing polarity. In order to secure a more continuous current flow, a number of ignitron tubes are used. Figure 123 shows a cutaway view of a commercial ignitron. The enclosure is metal and the water jacket surrounds it for cooling purposes, as the rate of current flow through the ignitron is so great that a large amount of heat is produced during normal operation. In addition to the essential parts shown in the cutaway view, there is usually an arrangement of baffles to prevent mercury from splashing on the anode. Mercury on the surface of the anode would emit electrons and defeat the purpose of the tube. Many commercial ignitrons are equipped with an auxiliary ignitor which functions only in event of failure of the main ignitor.

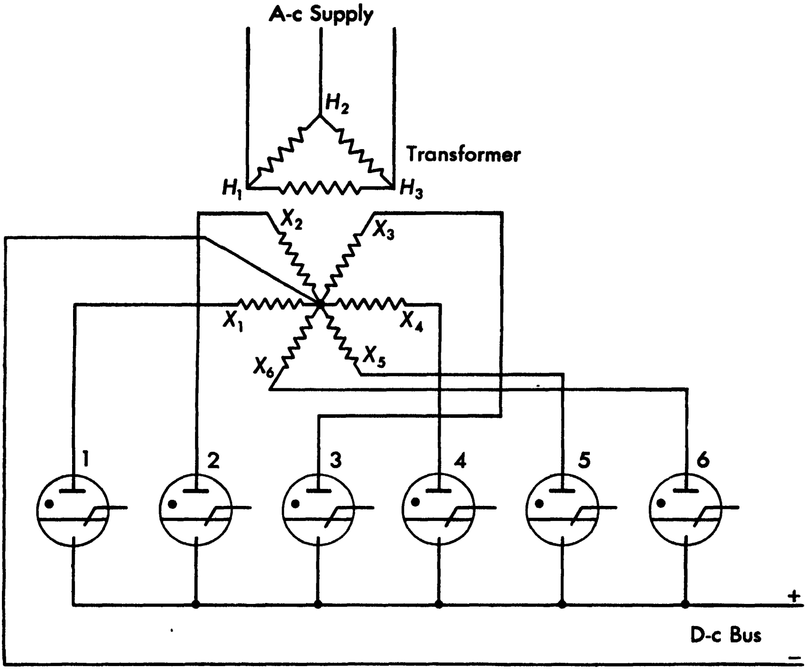


FIG. 124 Basic diagram of a typical Ignitron rectifier installation.

A typical commercial ignitron installation for use in an industrial plant requiring a source of direct current consists of six ignitron tubes.

Six tubes are used so that the resulting output is smooth, that is, nearly (but not completely) free from ripples. Power to these tubes is supplied from a three-phase alternating-current source through a transformer. The primary of the transformer is provided with three windings which are connected in delta. The secondary of this transformer is provided with six windings which are connected in star. Figure 124 shows the arrangement of these connections. The a-c supply enters at the top of the diagram and the d-c bus which supplies the plant is shown at the bottom. The excitation circuit which fires the ignitors at the proper instant is not shown in this diagram. This will be discussed separately. For maximum output, each ignitron is timed so that it will fire just at the instant its anode becomes positive. The firing, however, can be de-

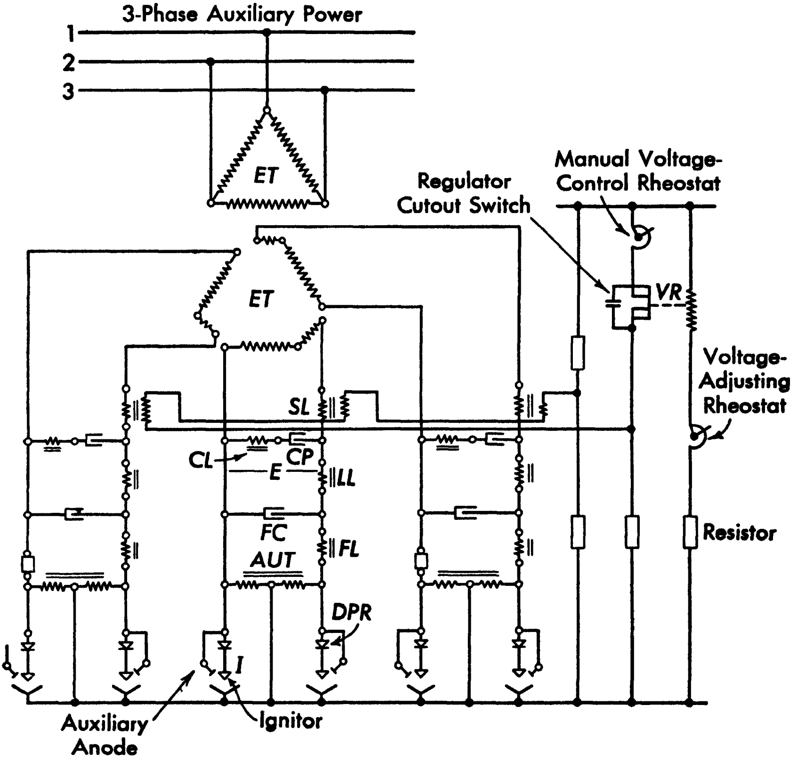


FIG. 125 Typical Unit Substation circuit diagram. (*General Electric Company*)

layed so that it occurs at any desired instant during the time the anode is positive. By thus regulating the firing time, the d-c output of the installation can be controlled.

The firing of the ignitron is controlled by the excitation circuit. Excitation circuits are numerous and rather complex. The circuit used by the General Electric Company in their Unit Substation is typical. A diagram of this circuit is shown in Fig. 125 and the symbols in the description which follows refer to those in this diagram.

The circuit consists entirely of static devices, such as reactors, capacitors, resistors, and small transformers. An understanding of these components is essential to an understanding of the operation of this circuit.

Each phase of the excitation circuit excites two ignitors whose anode voltages are 180 degrees apart in phase relation. The three-phase transformer bank (*ET*) consists of three single-phase control transformers, each having multiple secondary windings which provide a means of shifting the supply voltage into the proper relationship with respect to the main anode voltage. The remainder of each phase of the circuit consists essentially of two networks: (1) an adjustable phase shifting network which provides a convenient means of phase shifting the firing point, and consequently a means of adjusting the d-c voltage output of the rectifier; (2) a network for generating current impulses which, when fed to the ignitors, causes them to fire.

The adjustable phase-shifting network consists of: a saturable reactor (*SL*), a linear reactor (*CL*), and a capacitor (*CP*). The reactance of the saturable reactor is adjustable by means of d-c saturation. By changing the voltage drop across this saturable reactor, the phase angle of the voltage (*E*) is shifted with respect to the supply voltage. The adjustable phase shifting network is designed to cover a range corresponding to 15 per cent d-c voltage reduction at full load on the rectifier.

The network for generating current impulses consists of: a linear reactor (*LL*); a saturating reactor (*FL*); and a capacitor (*FC*). The linear reactor is designed to give constant reactance up to the rated voltage and frequency of the circuit. The saturating reactor is designed to saturate when the capacitor is charged to the maximum voltage, thus allowing this capacitor to discharge through the saturating reactor into the ignitor.

The dry plate rectifiers (*R*) prevent reverse current from flowing through the ignitors. The autotransformer (*AUT*) provides a return path for the ignitor currents and permits the firing of two ignitors which are in 180-degree phase relation, from one phase of the excitation circuit.

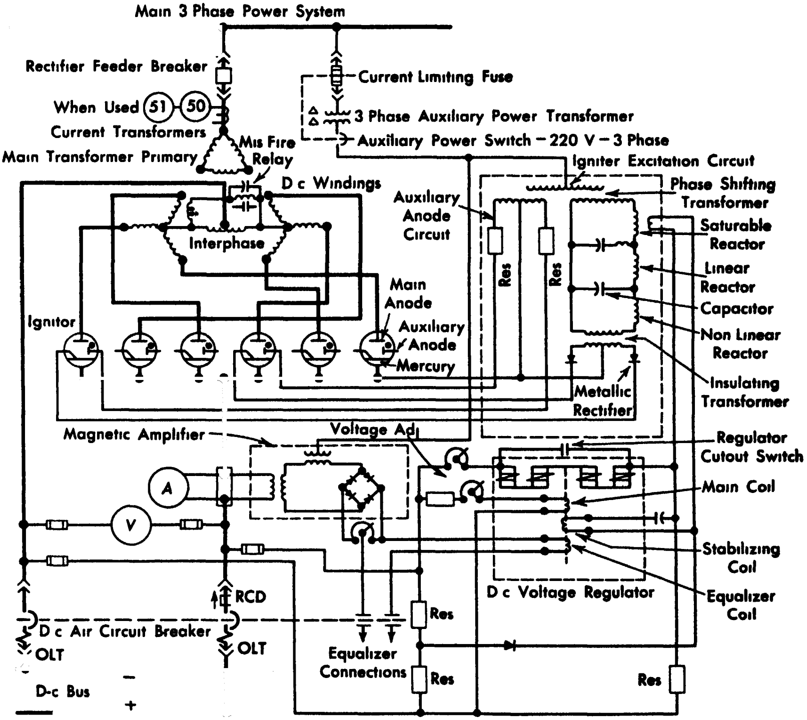


FIG. 126 Improved Unit Substation circuit diagram. (*General Electric Company*)

A newer circuit which is presently being used by the General Electric Company is shown in Fig. 126. This now supersedes the circuit shown in Fig. 125.

The Unit Substations of the General Electric Company are designed to operate from a three-phase primary supply of 2300 volts or 4000 volts. The d-c output is at 250 volts. Ratings presently range from 75 KW to 500 KW output.

The mercury-arc-type rectifier is becoming increasingly popular as a source of power for d-c equipment. A number of ignitron tubes are shown in Fig. 127. Once installed, this equipment requires much less attention than does a motor-generator set of like capacity. The electronic rectifier installation has a higher over-all efficiency, but in the final analysis, the choice between the motor-generator set and the electronic rectifier is largely one of economics.

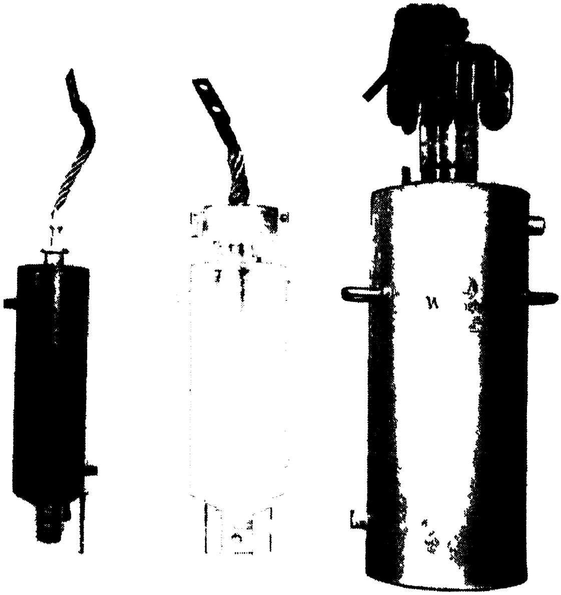


FIG. 127 Typical Ignitron tubes (*Westinghouse Electric Corp*)

CHAPTER 28 Electronic Speed Control

THE demands of modern industry require high-speed and precision control of manufacturing processes. Not only must the control be accurate, but also as nearly automatic as is humanly possible. It has long been recognized that the Ward Leonard system of d-c motor control is one of the most efficient for this purpose, but the installation of the necessary rotating equipment has prevented its use in all but certain specialized applications. With the development of industrial electronics, engineers soon realized that in the electronic tube they had a tool ideally suited to take over the functions of the motor-generator set of the Ward Leonard system. It was soon discovered that, in many instances, the desired purpose was accomplished even better than previously believed possible.

Speed control of the d-c motor is accomplished by the substitution of electronic devices for the motor-generator set and rheostats of the Ward Leonard system. The basic theory of the system remains unchanged; it is only the method of accomplishing the result that has become electronic.

The electronic tube most often used in motor control circuits is the *thyratron*. This is a grid-controlled gas-type electronic tube. Thyratrons usually contain three elements—anode, cathode, and control grid They are, however, not limited to three elements and multiple grid tubes are often found in certain types of motor control circuits. A heater is required in this type tube to raise the temperature of the cathode to such a point that it will readily emit electrons. The grid which usually surrounds the cathode acts much like a fence and blocks the flow of electrons to the anode as long as it is negative. When the grid becomes positive, it attracts the electrons and starts the current flow. Once the flow has started, the grid loses complete control. It therefore acts like a trigger. The actual firing point of the thyratron depends not only on the grid voltage, but also on the anode voltage.

It is important to remember that the grid of the thyratron can only start the flow of current, and once the current has started, it can not stop it. As was the case with the ignitron, the thyratron must be fired each time the anode becomes positive, as the current flow in the tube stops when the alternating current wave passes through zero. The output of the tube is controlled by an auxiliary circuit which regulates the instant of firing. This may be at any time during the cycle when the anode is positive. Thyratron tubes are used in the *Mot-O-Trol* system of the Westinghouse Electric Corporation and in the *Thy-Mo-Trol* system of the General Electric Company. These control systems are similar but not identical. While they differ in many details, the principal difference is the method by which the firing of the thyratron grids are controlled.

A pictorial representation of the Westinghouse *Mot-O-Trol* drive system is shown in Fig. 128. Controls for speed variation, starting, stopping, and reversing are on a separate push-button control station. Four pieces of equipment usually make up the installation. They are the power transformer, the electronic-control cabinet, the push-button control station, and the d-c motor itself. A shunt-wound motor is regularly supplied. Thyratrons supply the d-c motor with rectified a-c power. The rectified d-c voltage is applied to the shunt-wound d-c motor and may be varied from zero voltage to above rated voltage for armature-circuit control. Smaller thyratron tubes used in the control provide rectified d-c field current for the motor. The field voltage is held constant throughout the range of armature voltage and then reduced to provide greater speed range by field weakening.

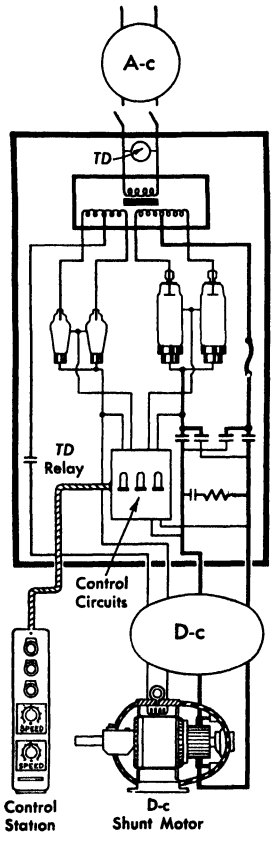


FIG. 128 Pictorial diagram of the Mot-O-Trol drive system. (*Westinghouse Electric Corp.*)

A schematic diagram of the *Mot-O-Trol* power circuit is shown in Fig. 129. The control circuits are entirely separate and are not shown here, as they are beyond the scope of this manual. An initial time-delay period is required to allow the tubes to warm up. The time-delay contacts are in the field-control and armature-control circuits so that the *forward* and *reverse* push buttons are not effective until the initial warm-up period is over. Once the line switch is closed, continuous heating of the tubes is maintained at all times, even though the drive may be idle for short periods of time. When the timing cycle has elapsed, full field voltage is automatically applied to the motor. Speeds may be preset on the control so that only the operation of the push button is necessary to obtain the predetermined speed in either the forward or reverse direction. Field weakening control, when used, is arranged so that the motor always starts with a full field regardless of the advance speed setting. The field is not weakened until after the motor reaches its base speed. Speed adjustments may also be made at any time while the motor is running. Speed control by varying armature or field voltage is obtained by advancing or delaying the firing point of the thyratron tubes on the a-c voltage wave. This permits only a certain portion of the wave to be rectified. This timing is accomplished by the auxiliary control circuit.

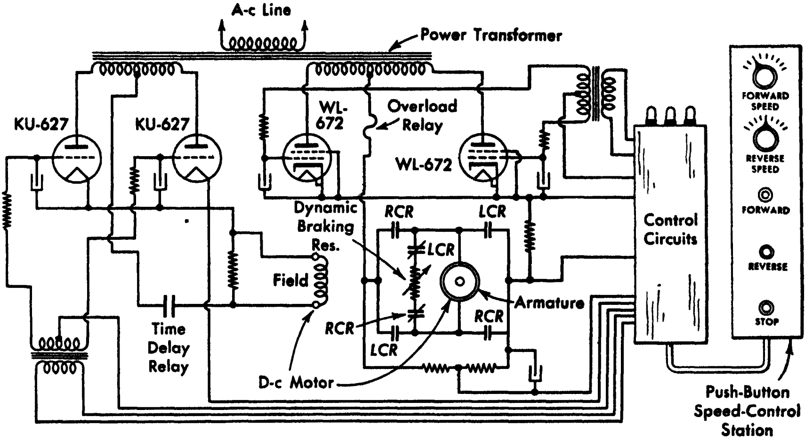


FIG. 129 Schematic diagram of the Mot-O-Trol power circuit. (*Westinghouse Electric Corp.*)

The control automatically regulates the motor speed so as to maintain essentially constant speed at any setting, regardless of changes in load. In a properly adjusted system, the speed over a 10 to 1 range will not vary more than 4 per cent from a presetting, with torque varying from no load to full load. Normal variations in a-c line voltage have only a small effect on the speed regulation.

The motor is quickly stopped with a dynamic braking resistor which is automatically inserted in the armature circuit when the stop button is pressed.

Controls of this type are usually provided with a number of protective devices designed to make the drive as nearly foolproof as possible. Anode fuses are provided to protect against damage resulting from short circuits, should they occur on the secondary side of the anode transformer. There is a current limit device limiting the output of the driven machine and, in addition, a thermal overload relay protects the motor against sustained overloads. A field loss relay will shut down the drive instantly in case the current of the motor field should be interrupted. In case of undervoltage or power failure, the anode contactor on the control panel drops out. This makes it impossible for the drive to restart without the operator's knowledge.

The electronic tubes used in the drive have a useful life of over 10,000 hours of continuous service. In most applications the tube life is from three to four years. The tubes are designed to handle the full-load current of the motor continuously. They will also handle up to 200 per cent of the motor's rating for short periods of time required during starting and accelerating.

Direct current motors used with electronic drives have frames somewhat larger than standard constant-speed d-c motors of the same horsepower and base speed rating. There are two reasons for this larger frame size: (1) the pulsating d-c supplied by the rectifier tubes causes greater heating of the motor than regular direct current; and (2) at low speeds, ventilation of the motor is materially reduced.

Where single-phase, full-wave rectification is used, the increase in frame size over the standard d-c motor for a given horsepower, and speed, is greater than where three-phase rectification is used. The number of rectified phases depends on the most economical arrangement of available thyratron tubes which will handle the horsepower requirements. The manufacturer of the control unit usually supplies the motor also, so that the most efficient combination is obtained.

With single-phase rectification, the probable over-all drive efficiency from the a-c power input to the d-c motor output will be about 50 per cent. With three-phase rectification, the efficiency will be approximately 60 per cent or greater. This compares with an efficiency of about 40 per cent for the Ward Leonard motor-generator system. Since the electronic drive consists of only static devices, its maintenance cost is considerably less than that of a motor-generator system.

Electronic drives are presently available in sizes from ¼ horsepower to 30 horsepower, with a standard speed range of about 20 to 1, or 1750 rpm to 88 rpm. Most manufacturers can supply other speed ranges for special applications, but it is recommended that standard speed ranges be used wherever possible. The entire electronic-drive system, including the motor, is sold as a "package" unit, which makes both selection and installation a comparatively simple matter.

CHAPTER 29 Control Maintenance

PROPER maintenance of electric control equipment is just as important as the maintenance of the motor itself. Such equipment often operates hundreds of times a day, and it is therefore important that it should be inspected regularly so that breakdown can be prevented before it occurs. Despite all which has been done to make control equipment nearly foolproof, a regular program of preventive maintenance is necessary if the equipment is to be kept operating at peak capacity. The first step in control maintenance is the establishment of a definite and regular inspection schedule. Such a schedule depends on the size of the plant, the number of control devices in service, and the frequency of their operation. The suggestions given here are therefore to be considered only as a general guide and should be adjusted to suit individual requirements.

Magnetic contactors should be checked at least once a month. Here is a check list of what to look for:

Control-circuit voltage
Collections of dirt or gum
Excess heating of parts as evidenced by discoloration of metal parts, charred insulation, or burning odor
Freedom of moving parts (no binding or sticking)
Corrosion of metal parts
Remaining wear allowance on contact tips
Excessive slam on pickup
Proper contact pressure
Proper contact alignment
Loose connections
Condition of flexible shunts
Condition of arc chutes or barriers
Worn or broken mechanical parts
Excessive arcing during operation
Condition of heating element on overload devices
Proper operation of time delay devices (where used)

In addition to the above list, manually operated starters should be checked for the following:

Stiffness of operation
Condition of face plate contact points
Wear or roughness on sliding contacts
Lubrication of arm and contacts (if recommended)
Operation of no-voltage release
Condition of resistors, evidenced by excessive heating
Burning of resistor terminals
Ventilation of resistor enclosure

If heavy dust or grease has accummulated on any part of the control, it should be removed with a heavy brush or wooden scraper. Dry dust and dirt should be blown off, using dry compressed air. This is important, as the dust may not only prevent the control devices from operating normally, but also may contain conducting material which will, ultimately, form a path between points of different potentials, resulting in a short circuit. Dust on the surface of mechanical interlocks may prevent a circuit from being completed even when the tips are

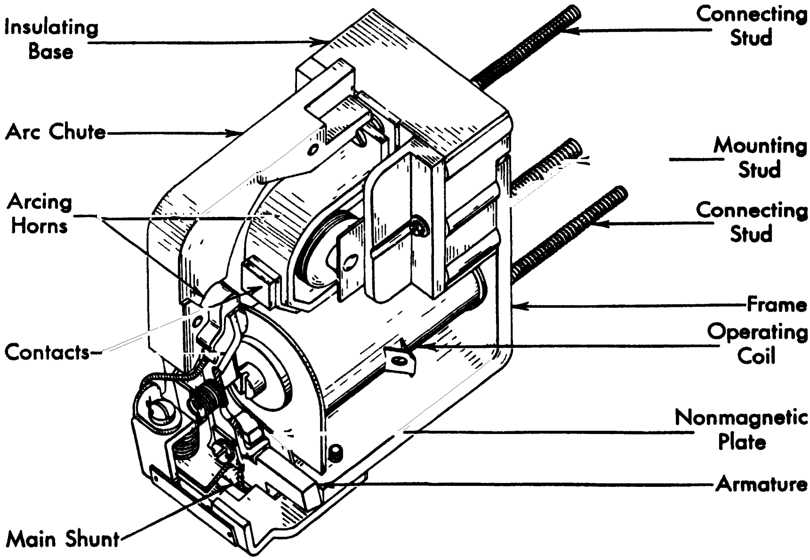


FIG. 130 A typical magnetic contactor. (*Westinghouse Electric Corp.*)

in closed position. Grease, oil, or sticky dirt are easily removed by applying cleaning fluid, such as carbon tetrachloride. Do not soak the parts, particularly the coils, with the cleaner, but use just enough to loosen the grease so that it can be wiped off. Remember that carbon tetrachloride is extremely toxic and should only be used in well-ventilated places. For cleaning small parts, a paint brush dipped into the cleaning solution is good for getting into corners and crevices.

A contactor has several bolted or spring closed contacts. If excessive heating is apparent, the most likely point of high resistance (and resultant heating) is where the movable tips make contact with the stationary tips. If copper oxide has formed, a few strokes with a file will remove the oxide and reduce the resistance to a low value again. It is usually unnecessary to file copper contacts if the device is operated fairly often. The slight abrasion produced by the ordinary closing operation is sufficient to keep the oxide cleaned off. Some contactors have tips made of special alloys which should never be filed. These usually are marked with a caution against filing.

A fairly common erroneous impression is that contact tips which have been roughened by service should be kept smoothed so that they will carry the load. A roughened tip will carry the current just as well as a smooth tip. A roughened tip should not be confused with one which is coated with copper oxide. If a copper tip becomes overheated, this condition indicates that oxide has developed and should be removed.

The contact-tip face should not be lubricated because the burning of the oil on circuit interruption increases the heating of the tip and shortens the life of the contact.

As the contact tip wears, pressure is maintained by the wiping spring, which presses the movable tip against the stationary tip when the contact is closed. Figure 131 illustrates the wear allowance and shows the wiping spring. Excessive heating may draw the temper of this spring and reduce the pressure of the contacts. The spring pressure on all poles of a given contactor should be approximately the same, and if one is considerably lower than the others, the spring should be replaced.

Many small contactors and relays are provided with fine silver tips which oxidize more slowly than copper tips. Silver oxide is a good electrical conductor, whereas copper oxide is not. It is therefore not necessary or advisable to file silver tips to remove the oxide. In fact the silver surface on a contact tip is very thin and filing may destroy it completely. Tips coated with silver are usually so marked, together with a warning to refrain from filing.

The operating coils on magnetic contactors are wound with very fine wire and should be handled with great care. The coil leads should never be used as carrying handles. Although the leads are generally strong enough to support the weight of the coil, this practice may cause a complete or partial fracture of the lead wire, resulting in either an open-circuited coil or one which may open-circuit shortly after being installed.

Direct-current shunt coils are particularly subject to failures caused by absorption of moisture from the air. When such a coil absorbs only a slight amount of moisture, the next operation of the coil may initiate electrolytic action between parts of different potential, which will quickly cause an open circuit. It is therefore important to keep the coils dry. If the coils have become wet, they should be removed from the contactor as soon as possible and thoroughly baked in an oven at a temperature of 110 C to 125 C. This should also be done if the coils have been soaked in carbon tetrachloride to remove grease and oil. The coils should then be painted, while still warm, with a good insulating varnish.

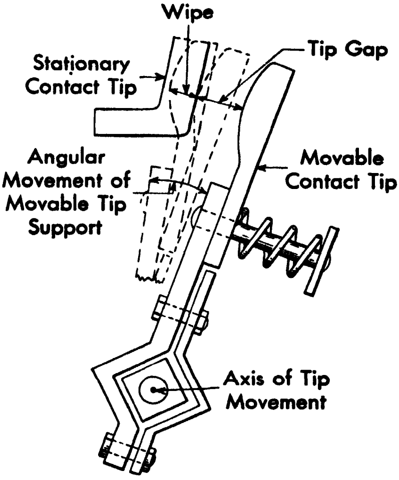


FIG. 131 Contact tip wear allowance. (*General Electric Company*)

In most types of manual face-plate controllers, the necessary resistors are mounted directly behind the face plate. These resistors are usually enclosed in a cage of wire mesh. Since it is normal for these resistors to dissipate considerable heat, it is important to see that there is a free circulation of air through the resistor cage. In the case of face-plate controllers which are used for starting duty only, the resistors are only in the circuit for a few seconds during the starting operation and seldom become very hot. Where such devices are used for speed control, the resistors are in the circuit for considerable periods of time and may become quite hot. Therefore, when examining such resistors, consideration should be given to the type of service for which they are to be used. Continual overheating of such resistors indicates that they are not suited for the application at hand, assuming, of course, that there are no loose connections and that everything else is in good order.

Resistors used in connection with the drum or cam type controllers and master controllers are usually located in a separate enclosure. This enclosure should be well ventilated and located in a dry place. Acid fumes will greatly shorten the life of resistors and should of course be avoided. Continual overheating generally indicates that a larger resistor should be installed.

TABLE **XI** Controller Trouble Chart

Symptom	Possible Cause	Suggested Remedy
CONTACTS: Overheating of contact tip	Copper oxide film on contact tip.	Install silver faced tips
		If copper tips, file with fine file
	Carrying load continuously for long time	Install silver faced tips or replace with larger device
	Sustained overload	Reduce current or install larger device
	Insufficient tip pressure	Clean and adjust pressure
		Check condition of springs
	Loose connections	Clean and tighten
Short tip life	Interrupting high currents	Install special tips designed to carry required current
	Excessive filing or dressing	Never file silver tips
		Avoid dressing simple rough spots
Weak tip pressure	Wear allowance gone	Replace tip and adjust
	Poor tip adjustment	Adjust gap and wipe
	Low voltage which prevents magnet sealing properly	Check line voltage
		Check voltage regulation and fluctuations

TABLE **XI** Controller Trouble Chart (*continued*)

Symptom	Possible Cause	Suggested Remedy
Welding or freezing of tips	Abnormal inrush currents of more than 10 times rating	Reduce currents
		Substitute special nonweld tips
		Install larger device
		Install copper tips if otherwise suited
COILS: Open circuit	Moisture or corrosive atmosphere	Relocate coils
		Use special resistant windings
	Mechanical damage	Do not handle coils by leads
		Coils should be firmly fastened in proper position
Roasted coil	Overvoltage	Check application and circuit
	Wrong type coil	Check with manufacturer for correct type
	Shorted turns caused by mechanical damage	Replace coil. Correct condition causing the trouble
Series coil overheats	Used above its current rating	Use larger coil. Check circuit and application
	Loose connections with surface oxidation	Tighten connections after first cleaning to remove oxide
SLIDING CONTACTS: Overheating	Over current, weak contact pressure, oxidation or rough contact surfaces	Check current rating.
		For heavy service use special alloy tips
		Lubricate as recommended by manufacturer
Roughening of contacts	Lack of maintenance and lubrication, very heavy service, arcing, oxidation or dirt	Sliding contacts will usually require some lubrication. Special alloy contacts should be used for heavy service

TABLE **XI** Controller Trouble Chart (*continued*)

Symptom	Possible Cause	Suggested Remedy
SLIDING CONTACTS (*Continued*): Arc chutes broken or pitted	Abnormal interrupting duty. Excess vibration or shock	Check application. Arc chutes are expendable and should be replaced periodically
Failure of manual starter to release	Mechanical binding	Adjust tension as recommended
	Gummy substances on magnet faces	Clean faces. Seek and eliminate cause
	Worn bearing	Replace worn part
	Nonmagnetic gap in magnetic circuit destroyed	Replace magnet
	Voltage not removed	Check coil voltage
	Not enough mechanical load on magnet	Check operation and adjust tension
RESISTORS: Overheating	Rating too low	Install larger resistor
	Running on starting duty resistor	Check circuit; check time-delay device, if any
	Restricted ventilation	Relocate to correct condition. Clean cage or mesh
Open circuit	Burned out from overheating	See Overheating above
	Corrosion or acid atmosphere	Relocate and protect from fumes
	Mechanical damage	Replace broken part
FUSES: Premature blowing	Fuse too small	Check circuit before installing larger fuses
	Heating at ferrules	Keep ferrules and clips clean
		Use plated clips. Replace clips
	Weak contact pressure	Provide adequate contact pressure

TABLE **XII** Electronic Control Trouble Chart

Symptom	Possible Cause	Suggested Remedy
Motor does not run	Time delay relay has not completed its normai cycle	Wait 5 minutes before trying to start motor again
	Time relay defective	Check relay and replace
	Open contractor coil	Check coil and replace
	Overload relay has tripped	Check cause of abnormal load. Armature circuit tube may be defective. Test tube
	Blown anode fuse	Check cause and replace fuse
	Defective field or armature control tube	Substitute tube known to be good for each tube in control
	Field failure relay drops out	Check field circuit including tubes. Replace any defective units
No control over speed of motor	Defective control tube	Substitute tube known to be good for each tube in control equipment
	Shorted grid capacitor	Check capacitor from grid to cathode on each Thyratron. Replace if necessary
	Speed control circuit	Check circuit for defective parts
	Speed control rheostat worn or burnt out	Replace with new speed control unit
	Dirty contacts on control relays	Clean surface of contact tips and check relay operation
Control smokes	Defective transformer	Replace transformer. Check filter capacitor for short
	Shorted capacitor	Replace capacitor
	Overheated dynamic braking resistor	Install larger resistor
Speed erratic	Thyratron tubes exceed rated temperature	More ventilation may be needed. Check tubes
	Voltage regulator tubes may be defective	Check tubes and replace as needed

Mention has been made in the electronic control trouble chart of defective or short-circuited capacitors. Defective capacitors can not be detected by mere visual inspection. They must actually be tested. Fortunately, there is a simple method of checking the condition of this unit.

Connect the capacitor in series with a battery and a voltmeter. Use a voltmeter with a scale which will read the full voltage of the battery. If the voltmeter shows a momentary defection at the instant the connection is made, the capacitor is usually a good one. A small constant defection on the meter indicates a leaky capacitor. If the full voltage of the battery is shown on the meter, the capacitor is short circuited. No defection at all, even at the instant the connection is made, indicates an *open* circuit.

CHAPTER 30 Resistors and Rheostats

THE majority of d-c motor applications involve the use of resistors and rheostats. There are times when these units must be replaced or modified to alter the starting or speed characteristics of the motor. How to select the proper unit to bring about the desired characteristics is therefore of great importance.

Since resistors and rheostats are rated commercially by their resistance in ohms, and their safe current-carrying capacity in amperes, it is necessary to calculate both of these values for the particular application. Some units are rated in watts rather than in amperes, but if either of these quanities are known, the other can easily be found by use of Ohm's law. Ohm's law states that the current in a d-c circuit is directly proportional to the electromotive force and inversely proportional to the resistance. This can be written as

$$I \text{ (current)} = \frac{E \text{ (electromotive force)}}{R \text{ (resistance)}} \qquad (15)$$

or

$$E = IR$$

Power in watts (W) is given as

$$W = EI$$

Substituting E for its value as given by Ohm's law in the expression just given for power in watts, we have

$$W = IR \times I, \text{ or } W = I^2R \qquad (16)$$

Table XIII gives the various ways of expressing Ohm's law when any two of the three quantities involved are known. The symbols given in this table refer to the practical units of electricity which are

E (electromotive force) = Volts
I (current) = Amperes
R (resistance) = Ohms
W (power) = Watts

When a number of resistors are connected in series, the total resistance of the circuit is found by simple addition.

$$R \text{ (total resistance)} = R_1 + R_2 + R_3 + R_4, \text{ etc.} \tag{17}$$

If, however, the resistors are connected in parallel, the total resistance of the circuit is reduced, as each resistor in parallel provides another path for the current to flow. In this case, the total resistance of a number of units connected in parallel is

$$R \text{ (total resistance)} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}, \text{ etc.}} \tag{18}$$

The first step in the selection of a resistor is the determination of its resistance in ohms. The method of making this determination depends on the service required and upon the characteristics of the motor with which it is used.

TABLE **XIII** Ohm's Law

TO FIND	USING THESE TWO QUANTITIES					
	E & I	I & R	E & R	W & R	W & E	W & I
W	EI	I^2R	$\frac{E^2}{R}$			
E				$\sqrt{WR}$		$\frac{W}{I}$
I			$\frac{E}{R}$	$\sqrt{\frac{W}{R}}$	$\frac{W}{E}$	
R	$\frac{E}{I}$				$\frac{E^2}{W}$	$\frac{W}{I^2}$

A common application of resistors is for starting a shunt wound motor. It has already been mentioned several times that if a shunt motor, at rest, is connected directly to the supply line, the initial inrush of current would be limited only by the resistance of the armature circuit which is very low. It is therefore necessary to insert one or more resistors in the circuit to limit this initial rush to a safe value. To compute the amount of resistance to be inserted, it is first necessary to assume a safe value for the inrush current. This value is generally assumed to be 150 per cent to 175 per cent of the normal full-load current. The method of computing the amount of resistance in ohms needed to start a given motor is best shown by a numerical example.

Suppose that it is desired to start a 50 horsepower, 230 volt d-c motor whose normal full-load current is 180 amperes. This information is taken from the name plate of the given motor. Now in starting this motor, it is desired to limit the inrush current to 175 per cent of the normal full-load current. This is 315 amperes. The problem is now to find the values of resistances needed so that the current at no time exceeds 315 amperes.

To limit the current to 315 amperes at 230 volts, the total amount of resistance which should be in the circuit at the instant of starting should be

$$R \text{ (total)} = \frac{230}{315} = .73 \text{ chms}$$

This figure represents the total resistance of both the motor itself and the external resistor. To find the amount of external resistance required, it is necessary to subtract the internal resistance of the motor from this figure.

Now, as the motor accelerates, it generates a counter electromotive force so that the effective voltage is reduced. This in turn reduces the line current. When the line current falls to a value of 180 amperes (the normal rated current), the effective voltage, by Ohm's law, is

$$.73 \times 180 = 131 \text{ volts}$$

Using this effective voltage, the resistance in the circuit can be reduced to a new value which will again allow 315 amperes to flow. To find the value of this new resistance, the original Ohm's law computation is repeated using this new value of the voltage, 131 volts. This is

$$R \text{ (total)} = \frac{131}{315} = .418 \text{ ohms}$$

The total resistance in the motor circuit can now be reduced to this new value (.418 ohms) and the motor speeds up. Again, due to the increase of speed, the counter electromotive force increases so that the effective voltage is further reduced. The new value of the effective voltage, when the current has again dropped to the normal 180 amperes is

$$.418 \times 180 = 75 \text{ volts.}$$

The calculation is again repeated, using this new voltage and the maximum value of the current to determine the new amount of resistance

$$R \text{ (total resistance)} = \frac{75}{315} = .238 \text{ ohms}$$

With this new resistance in the circuit, the effective electromotive force at 180 amperes normal rated current is

$$.238 \times 180 = 42.8 \text{ volts}$$

Again the calculation is repeated to find the new resistance

$$R \text{ (total resistance)} = \frac{42.8}{315} = .136 \text{ ohms}$$

This indicates that the total resistance now needed in the armature circuit is only .136 ohms. Since this value is just about that of the armature of a 50 horsepower 230 volt shunt motor, no further external resistance is needed and the motor is connected directly across the supply line. Tabulating the resistances just computed, we find

1st resistance = .75 ohms
2nd resistance = .418 ohms
3rd resistance = .238 ohms
4th resistance = .136 ohms

Therefore, to start the motor in question, the first step of the controller should reduce the total resistance from .75 ohms to .418 ohms. The second step reduces it from .418 ohms to .238 ohms, and so on through the fourth step. It should be again pointed out that these figures represent *total* resistance of the combined motor and external circuits. To find the value of the external resistor steps alone, it is necessary to subtract the resistance of the armature circuit.

After the resistance values have been selected, there is still one further consideration: the amount of current which the resistors are required to carry. In this example, it was assumed that this current would not exceed 315 amperes. Therefore, a resistor of the proper ohmic value capable of handling 315 amperes during the starting period should be selected. This is not difficult as the starting period is very brief.

The problem of selection of a rheostat for armature speed control is not so involved. In making the calculation for the amount of resistance required in the armature circuit to reduce the motor speed to a given value, it can be assumed that the field current is constant and the effects of armature reaction can be neglected.

Assume a 20 horsepower 230 volt shunt motor whose armature resistance is .15 ohms. When this motor operates at no load, the armature current is 3 amperes. The full-load current is 75 amperes. The speed at no load is 1220 rpm. It is desired to select a rheostat which will reduce the speed to 600 rpm, roughly a 50 per cent reduction.

It is first necessary to determine the armature counter electromotive force at no load. This is slightly less than the line voltage. It is equal to $230 - (3 \times .15) = 229.5$ volts. Since the speed of a motor is directly proportional to the counter electromotive force (see Chap. I), the counter electromotive force at 600 rpm can be found from

$$\frac{E}{229.5} = \frac{600}{1220}, \text{ or } E = \frac{600 \times 229.5}{1220} = 113 \text{ volts}$$

The effective armature voltage is 230 − 113, or 117 volts. The problem is now to find a suitable rheostat which will reduce the armature voltage to 117 volts at the full-load current of 75 amperes. By Ohm's law

$$\frac{117}{75} = 1.56 \text{ ohms (total resistance)}$$

Since the resistance of the armature circuit itself is .15 ohms, the required external resistance is $1.56 - .15 = 1.41$ ohms. Therefore to reduce the speed of this motor to 600 rpm, the armature circuit rheostat should have a resistance of 1.41 ohms. Now, had it been assumed that the armature voltage at no load was that of the full-line voltage, 230 volts, instead of the computed value of 229.5 volts, there would have been very little difference in the final value of the external resistance. For most practical purposes, this assumption can usually be made.

The selection of the proper field rheostat to obtain motor speeds above normal rating involves so many factors that it is recommended that the motor manufacturer be consulted. For example, at the instant the field is weakened, the counter electromotive force induced in the armature drops and there is a sudden inrush of current. A field rheostat must be selected to keep this inrush current within safe limits. Arcing between contacts on the face of the field rheostat may be excessive, if the values of the resistance between each point on the rheostat are not properly spaced. While the motor speed varies in inverse proportion to the field flux, the available flux does not always vary directly with the field current. Magnetic leakage, magnetic saturation, and many similar factors all influence the relationship between field current and available flux. These factors must all be considered in the selection of the field rheostat. As an approximation, however, it may be stated that the field rheostat resistance is about equal to two-thirds of that of the motor field when a 25 per cent speed increase is wanted. It may be up to 10 or 12 times that of the field when large increases are wanted. To keep the current inrushes to a safe value, plate-type field rheostats have from 40 to 60 steps. Rheostats for very large motors may have from 100 to 150 steps. The current capacity of a field rheostat should change by approximately equal amounts as each step of resistance is inserted. The watt capacity of a field rheostat is the sum of the watt capacities of the individual steps.

Low-resistance, high-current capacity resistors are usually in the form of cast iron grids. These grids are mounted in stacks on steel rods. Mica tubing is used to insulate the rods, and mica washers are used as insulating spacers between grids. Such grids are physically strong and will stand considerable heat. The resistance of the cast iron grid depends on its cross section and the length of the electrical path through the grid.

Another type of resistance, where current values are not so great, is the ribbon-type resistor. The ribbon is made of a strip of resistance alloys such as nichrome, and may be either wound edgewise on porcelain tubes or stretched back and forth between insulated supports. Such resistors are lighter in weight than cast iron grids and will stand more vibration and jarring.

Wire-wound resistors are used in low-current applications where high-resistance units are required. Some forms of wire-wound resistors are baked on porcelain tubes after being covered with a heat-resistant enamel, while others are merely open wound on porcelain tubes. This type of resistor is available in a wide range of resistance values, but all have a comparatively limited current-carrying capacity.

A table of a few of the more common commercial alloy materials used as resistors is given in the Appendix. The approximate composition and comparative restivity of each is indicated.

CHAPTER 31 Mechanical Drives

THE manner in which an electric motor is connected to the driven load deserves careful consideration. Failure to select and maintain the proper type of drive will greatly lower the over-all operating efficiency of the equipment.

In the earliest mechanized industrial development, it was necessary to drive individual machines by belts from a long overhead line shaft. This line shaft was driven by a suitable steam engine. With the advent of electric power, it was a comparatively simple matter to replace the steam engine with an electric motor, leaving the remainder of the existing drive system unchanged. The modern trend, however, is to replace the long line shaft with individual electric motors. This greatly increases the plant efficiency and reduces hazards and maintenance costs.

Motors may be directly coupled to the driven machine if the speed requirements are suitable. Coupling arrangements of various types are available, some flexible and some rigid, depending on the type of the driven machine. Where the operating speed of the driven machine differs from that of the motor, the drive connection may be made by flat belt, V-belt, silent chain, or direct gearing.

Most widely used is probably the flat leather belt. This is made of oak tanned leather and is tough and long lasting. Its pulley-gripping capacity tends to increase with increased loads and it is able to absorb shocks due to sudden changes in operating conditions. The horsepower transmitted by leather belting depends on its width, thickness, linear speed, size of pulleys, type of motor, and the nature of the driven load.

The speed of any belt, in feet per minute, can be computed from

$$\text{Speed} = 0.262 \times \text{dia. pulley} \times \text{rpm} \qquad (19)$$

Where pulleys of different size are used, the pulley diameter (in inches) and the rpm of the same pulley should be used in making the computation. For d-c motor drives, this speed should not exceed 5,000 feet per minute. High speeds increase the centrifugal force and lessen the grip of the belt on the pulley.

With the linear speed of the belt established, the horsepower per inch of width can be found from Table XIV, supplied by the American Leather Belting Association. This table gives a theoretical value only and must be corrected to cover actual conditions. Suggested correction factors cover the type of motor, the size of pulley, and special operating conditions. These are:

Factor M (for the Motor)

Shunt-wound motors	1.5
Compound-wound motors	2.0

Factor P (for the Pulley)

Dia. of small pulley in inches	
4 and under	0.5
4½ to 8	0.6
9 to 12	0.7
13 to 16	0.8
17 to 30	0.9
Over 30	1.0

Using these correction factors, the horsepower rating of a flat leather belt may be computed from

$$HP = \frac{\text{Width} \times P \times (\text{Theoretical } HP)}{M} \tag{20}$$

or with the horsepower known, the width of a leather belt can be obtained from

$$\text{Width} = \frac{\text{Motor } HP \times M}{\text{Theoretic } HP \times P} \tag{21}$$

Under special operating conditions such as jerky loads, bad atmospheres, and sudden reversing loads, it is suggested that from 25 to 50 per cent be added to the computed width of the belt.

To compute the length of a belt when pulleys of different size are involved, the standard formula is

$$\text{Length} = 2C + 1.57(D + d) + \frac{(D - d)^2}{4C} \tag{22}$$

TABLE XIV Theoretical Horsepower per Inch of Width

(American Leather Belting Association)

Belt Speed Feet per Min.	SINGLE PLY		DOUBLE PLY			TRIPLE PLY	
	11/64″ Med.	13/64″ Heavy	18/64″ Light	20/64″ Med.	23/64″ Heavy	30/64″ Med.	34/64″ Heavy
600	1.1	1.2	1.5	1.8	2.2	2.5	2.8
800	1.4	1.7	2.0	2.4	2.9	3.3	3.6
1000	1.8	2.1	2.6	3.1	3.6	4.1	4.5
1200	2.1	2.5	3.1	3.7	4.3	4.9	5.4
1400	2.5	2.9	3.5	4.3	4.9	5.7	6.3
1600	2.8	3.3	4.0	4.9	5.6	6.5	7.1
1800	3.2	3.7	4.5	5.4	6.2	7.3	8.0
2000	3.5	4.1	4.9	6.0	6.9	8.1	8.9
2200	3.9	4.5	5.4	6.6	7.6	8.8	9.7
2400	4.2	4.9	5.9	7.1	8.2	9.5	10.5
2600	4.5	5.3	6.3	7.7	8.9	10.3	11.4
2800	4.9	5.6	6.8	8.2	9.5	11.0	12.1
3000	5.2	5.9	7.2	8.7	10.0	11.6	12.8
3200	5.4	6.3	7.6	9.2	10.6	12.3	13.5
3400	5.7	6.6	7.9	9.7	11.2	12.9	14.2
3600	5.9	6.9	8.3	10.1	11.7	13.4	14.8
3800	6.2	7.1	8.7	10.5	12.2	14.0	15.4
4000	6.4	7.4	9.0	10.9	12.6	14.5	16.0
4200	6.7	7.7	9.3	11.3	13.0	15.0	16.5
4400	6.9	7.9	9.6	11.7	13.4	15.4	16.9
4600	7.1	8.1	9.8	12.0	13.8	15.8	17.4
4800	7.2	8.3	10.1	12.3	14.1	16.2	17.8
5000	7.4	8.4	10.3	12.5	14.3	16.5	18.2
5200	7.5	8.6	10.5	12.8	14.6	16.8	18.5
5400	7.6	8.7	10.6	12.9	14.8	17.1	18.8
5600	7.7	8.8	10.8	13.1	15.0	17.3	19.0
5800	7.7	8.9	10.9	13.2	15.1	17.5	19.2
6000	7.8	8.9	10.9	13.2	15.2	17.6	19.3
Minimum Pulley Diameter: Belts Under 8″ Wide	3″	5″	6″	8″	12″	20″	24″
Minimum Pulley Diameter: Belts 8″ Wide and Over			8″	10″	14″	24″	30″

These are the minimum allowable pulleys for the above thickness belts.

where

Length is expressed in inches.
D is the diameter of the larger pulley in inches.
d is the diameter of the smaller pulley in inches.
C is the distance between pulley centers in inches.

Before a new belt is installed, the shafts should be checked with a level and the pulleys aligned. Figure 132 shows a motor base with provision made for aligning. For best result with a leather belt, the least amount of tension needed to transmit the load should be used. Horizontal belts should be operated with the slack side on top as in Fig. 133, in order to increase the arc of contact between the pulley and belt.

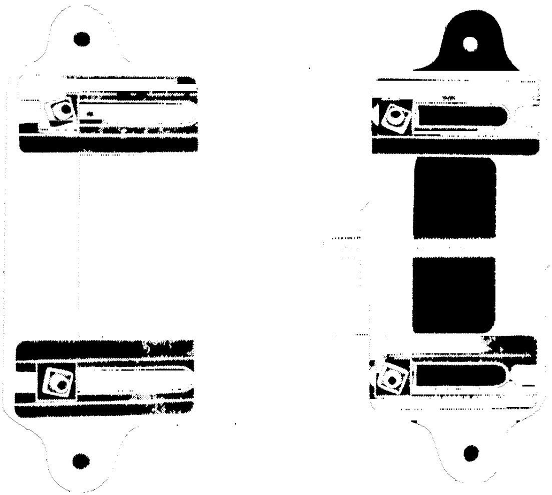


FIG. 132 Adjustable base for motor mounting. (*Century Electric Co.*)

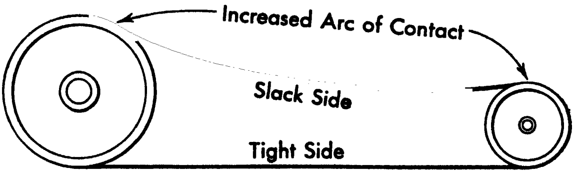


FIG. 133 Correct arrangement for a belt drive.

Maximum pulling power is obtained by running the grain or hair side of the belt next to the pulley.

Leather belting should be kept as clean as possible. Oil and grease reduce the belt life and pulling power. If regular wiping is not sufficient to keep the belt free from dirt, it should be removed and thoroughly scrubbed with a degreasing solution. Following cleaning, a leather belt should be treated with an approved belt dressing designed to supply the necessary natural oils which the belt may have lost in use or during cleaning. Leather belts have a long useful life only when properly cared for.

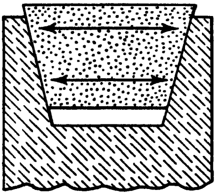


FIG. 134 Cross section showing contact area of a V-belt.

Another extensively used drive is the V-belt. This is a rubberized fabric material molded with sloping sides so that its cross section resembles the upper part of the letter V. The sides of the belt, rather than the bottom, make contact with the pulley. A grooved sheave instead of a flat pulley must be used. The area of contact is indicated in Fig. 134. As the belt bends around the sheave, it has a natural tendency to bulge at the sides. This bulge is confined by the rigid V-shaped grooves of the sheave. This results in high-pressure contact between the sides of the belt and the groove walls, thus producing a strong vice-like grip.

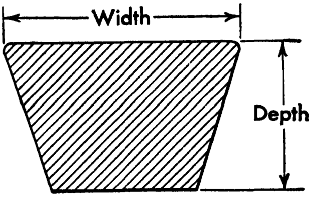


FIG. 135 Cross section of a V-belt showing where measurements are taken.

The V-belt is commercially available in five standard sizes, each designated by letter, as shown in Table XV. These sizes and designations are standard with the belting industry and vary only slightly between different makers.

A number of V-belts on a multiple-grooved sheave is used to power large loads. Should one or more belts fail on such a drive, the remainder will continue to operate until the necessary replacements can be made. The motor in Fig. 136 is provided with a multiple-groove sheave and adjustable base.

The selection of the proper V-belt involves so many variable factors that it is impossible to give definite recommendations here. Belt makers publish extensive handbooks giving detailed tables indicating the size, type, and number of V-belts needed for transmitting the required horsepower under a variety of service conditions. It is suggested that one of these be consulted.

TABLE **XV** Standard Sizes of V-Belts

Designation	Width (W)	Depth (D)
A	1/2	11/32
B	21/32	7/16
C	7/8	9/16
D	1 1/4	3/4
E	1 1/2	1

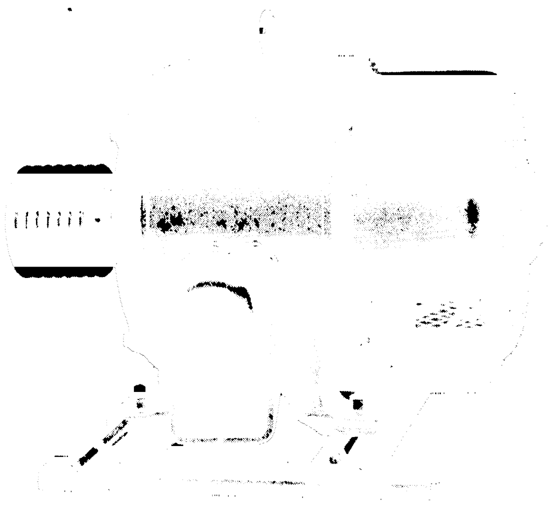


FIG. **136** Motor on adjustable base with grooved pulley for V-belt drive. (*Allis-Chalmers Mfg. Co.*)

Before installing a V-belt, the sheaves and shaft should be checked for alignment. The motor is then moved forward on its base (See Fig. 132) to permit placing the V-belts in the grooves. The motor is then moved backward until the proper tension is obtained. This can be determined by striking the belt with the hand. When too much slack exists, the resulting vibration will feel dead. When proper tension is reached, the belt will have a live springy response.

Belt dressings are not required with V-belts and should never be used. The only maintenance necessary is to keep them clean and avoid overheating. Worn belts should be replaced promptly. On multiple V-belt drives it is recommended that all belts be replaced at one time, otherwise the load may not be properly distributed between belts.

Chain drives are more positive than belt drives. They are used where slippage under varying loads is undesirable. Chain drives are noisier than belt drives and should not be operated at speeds above 1500 feet per minute. Both the initial cost and maintenance of the chain drive is greater than that of the belt drive. Its application is justified only where it is essential to avoid slippage.

CHAPTER 32 Code Requirements

THE National Electric Code, which is the standard of the National Board of Fire Underwriters, sets forth certain rules and regulations covering the installation and application of electrical equipment. These regulations do not cover the performance standards of the equipment. Performance standard and methods of testing apparatus to determine whether or not they meet with such standards are published by the American Institute of Electrical Engineers, the National Electrical Manufacturers Association, and the American Standards Association. The National Electric Code is primarily a safety code designed for the protection of life and property from electrical hazards.

In this chapter, the pertinent rules covering direct current motors as given in the 1947 edition of the Code are outlined by permission of the National Board of Fire Underwriters. It should be pointed out and strongly emphasized that what is given here are merely extracts and excerpts taken from the Code, and no pretense is made that they are complete. If further details are required, a complete copy of the latest edition of the National Electric Code should be obtained and given careful study. Copies of the National Electric Code are obtainable from any branch office of the National Board of Fire Underwriters, the National Fire Protection Association, the American Standards Association, and many local insurance underwriters. The Code is constantly undergoing revision and it is important to secure the latest edition. Many communities have adopted the provisions of the National Electric Code, and they provide by law that all electrical installations must be made in accordance with the requirements of the Code. The Article numbers and Table numbers given are those of the 1947 edition of the Code.

EXTRACTS FROM 1947 EDITION NATIONAL ELECTRIC CODE

(Pertaining to d-c Motors)

Article 430

Motors and Controllers

4301 General. It is intended that the following general provisions shall cover all provisions for motors and controllers which do not properly fall into the other divisions of this Article.

4302 Application of Other Articles. Motors and controllers shall also comply with the provisions of the following:

. . . . .

Cranes and Hoists	Article 610
Elevators	Article 620
Garages	Section 5103
Hazardous Locations	Article 500

. . . . .

4303 Overheating from Dust Accumulations. In locations where dust or flying material will collect on or in motors in such quantities as to seriously interfere with ventilation or cooling of motors and thereby cause dangerous temperatures, suitable types of enclosed motors . . . shall be used . . .

4304 Identification of Motors. A motor shall be provided with a name plate which shall give the maker's name, the rating in volts and amperes . . . the normal full load speed and the interval during which it can operate at full load starting cold, before reaching its rated temperature. . . . A motor provided with a protective device integral with the motor . . . shall have a marking which will so indicate. . . .

4305 Identification of Controllers. A controller shall be marked with the maker's name or identification symbol, the voltage, the current or horsepower rating and such other data as may be needed to properly identify the motors for which it is suitable. . . .

4306 Identification of Terminals. Terminals of motors and controllers shall be suitably identified, as by marking or color, where necessary to indicate the proper connections.

4307 Wiring Space in Enclosures. Enclosures for controllers and disconnecting means for motors shall not be used as junction boxes, troughs, or raceways for conductors feeding through or tapping off to other apparatus unless designs are employed which provide adequate space for this purpose.

4308 Enclosures. Suitable guards or enclosures shall be provided to protect exposed current-carrying parts of motors and the insulation of motor leads where installed directly under equipment, or in other locations where dripping or spraying oil, water, or other injurious liquid may occur, unless the motor is designed for the existing conditions.

4309 Current Carrying Capacities. Whenever the current rating of a motor is used to determine the current carrying capacity of conductors, switches, branch circuit overcurrent devices, etc., the values given in . . . Table 21 . . . shall be used in lieu of actual current rating marked on motor name plates. . . . Motor running overcurrent protection shall be based on the motor name plate current rating. If a motor is marked in amperes, but not horsepower, the horsepower rating shall be assumed to be that corresponding to the value given in Table 21 . . . , prorated if necessary.

4310 Location of Motors. Motors shall be located so that maintenance such as lubrication of bearings and replacing of brushes can be readily accomplished. Open motors having commutators or collector rings shall be located or protected so that sparks cannot reach adjacent combustible material. This does not prohibit the installation of these motors on wooden floors or supports.

Code Table 21 Full Load Currents—Direct Current Motors

H.P.	115 V.	230 V.	550 V.
½	4.6	2.3	
¾	6.6	3.3	1.4
1	8.6	4.3	1.8
1½	12.6	6.3	2.6
2	16.4	8.2	3.4
3	24	12	5.0
5	40	20	8.3
7½	58	29	12.0
10	76	38	16.0
15	112	56	23.0
20	148	74	31
25	184	92	38
30	220	110	46
40	292	146	61
50	360	180	75
60	430	215	90
75	536	268	111
100		355	148
125		443	148
150		534	220
200		712	295

These values for full-load current are average for all speeds.

Size of Conductors for Motor Circuits

4311 General. It is the intent of the following provisions to specify sizes of conductors capable of carrying the motor current without overheating under the conditions specified.

4312 Individual Motors. Branch circuit conductors supplying an individual motor shall have a carrying capacity not less than 125 per cent of the motor full load current rating; provided, that conductors for motors used for short time, intermittent, perodic, or varying duty, may have a carrying capacity not less than the percentage of the motor name plate current rating as shown in the following table. . . .

	PER CENT OF NAME-PLATE CURRENT RATING			
Classification of Service	5 Minute rating	15 Minute rating	30 & 60 Min. rate.	Continuous rating
Short time duty	110%	120%	150%	
Intermittent duty	85%	85%	90%	140%
Periodic duty	85%	90%	95%	140%
Varying duty	110%	120%	150%	200%

Definitions of Service Classification

(Taken from Article 100)

Short Time Duty: Short time duty is a requirement of service that demands operation at a substantially constant load for a short and definitely specified time. Examples: Operating valves, raising or lowering rolls, etc.

Intermittent Duty: Intermittent duty is a requirement of service that demands operation for alternate intervals of (1) load and no-load; or (2) load and rest; or (3) load, no-load and rest. Examples: Freight and passenger elevators, tool heads, pumps, drawbridges, turntables, etc.

Periodic Duty: Periodic duty is a type of intermittent duty in which the load conditions are regularly recurrent. Examples: Rolls, ore and coal handling machines, etc.

Varying Duty: Varying duty is a requirement of service that demands operating at loads, and for intervals of time, both of which may be subject to wide variation.

4314 Conductors Supplying Several Motors. Conductors supplying two or more motors shall have a current carrying capacity of not less than 125% of the full load current rating of the highest rated motor in the group plus the sum of the full load current ratings of the remainder of the motors in the group.

Motor Overcurrent Protection

4321 General. The following provisions specify overcurrent devices intended to protect the motors; the control apparatus, and the branch circuit conductors against excessive heating due to motor overloads.

4322 Continuous Duty Motors. Each continuous duty motor shall be protected against running over-current as follows:

a) More than One Horsepower: For a motor rated at more than one horsepower, this protection shall be secured by use of one of the following means:

1. A separate overcurrent device which is responsive to motor current. This device shall be rated or set at not more than 125% of the motor full load current rating for an open type motor marked to have a temperature rise not over 40 C, and at not more than 115% for all other type motors . . .

2. A protective device integral with the motor which is responsive to motor current or to both motor current and temperature. . . . If the motor current interrupting device is separate from the motor and its control circuit is operated by a protective device integral with the motor, it must be so arranged that the opening of the control circuit will result in interruption of current to the motor.

b) One Horsepower or Less, Manually Started. Any motor of one horsepower or less which is manually started and which is within sight from the starter location, shall be considered as protected against overcurrent by the overcurrent device protecting the conductors of the branch circuit. . . .
(A distance of more than 50 feet is considered equivalent to being out of sight)

c) One Horsepower or Less, Automatically Started. Any motor of one horsepower or less which is started automatically shall be protected against overcurrent by use of one of the following means:

1. A separate overcurrent device which is responsive to motor current. This device shall be rated or set at not more than 125% of the motor full load current rating for an open type motor marked to have a temperature rise of not over 40 C and at not more than 115% for all other types of motors. . . .
2. A protective device integral with the motor which is responsive to motor current or to both motor current and temperature. . . . If the motor current interrupting device is separate from the motor and its control circuit and its control circuit is operated by a protective device integral with the motor, it must be so arranged that the opening of the control circuit will result in interruption of current to the motor. . . .

4324 Selection or Setting of Protective Device. Where the values specified for motor running overload protection do not correspond to the standard sizes or ratings of fuses, non-adjustable circuit breakers, thermal cutouts, thermal relays, the heating elements of thermal trip motor switches . . . the next higher size rating or setting may be used, but not exceeding 140% of the full load current rating . . .

4325 Shunting During Starting Period. If the motor is manually started, the running overcurrent protection may be shunted or cut out of the circuit during the starting period of the motor, provided the device by which the overcurrent protection is shunted or cut out cannot be left in the starting position, and the motor shall be considered as protected against overcurrent during starting period if fuses or time delay circuit breakers rated or set at not over 400% of the full load current of the motor, are so located in the circuit as to be operative during the starting period of the motor. The motor running overcurrent protection shall not be shunted or cut out during the starting period if the motor is automatically started.

4326 Fuses, in Which Conductor. If fuses are used for motor running protection, a fuse shall be inserted in each ungrounded conductor.

4327 Devices Other than Fuses, in Which Conductor. If other than fuses are used for motor running protection, the following . . . shall govern the minimum number and location of overcurrent units such as trip coils. relays, or thermal cutouts.

2 wire ungrounded supply—1 in either conductor.
2 wire, 1 conductor grounded—1 in either ungrounded conductor.
3 wire grounded neutral—1 in either ungrounded conductor.

. . . . .

4329 Motor Controller as Running Protection. A motor controller may also serve as the running overcurrent device if the number of overcurrent units complies with the foregoing section 4327; and if these overcurrent units are operative in both starting and running position. . . .

4330 Thermal Cutouts and Relays. Thermal cutouts, thermal relays and other devices for motor running protection, shall be protected by fuses or circuit breakers with ratings or settings of not more than four times the rating of the motor for which they are designed, unless approved for group installation and marked to indicate the maximum size of fuse by which they must be protected.

4331 Rating of Protective Devices. Motor running overcurrent devices other than fuses shall have a rating of at least 115% of the full load current rating of the motor.

4332 With Lamps or Receptacles. [Author's Note: This section concerns motor protection when used on branch circuits which also supply lamps and receptacles.]

4333 Automatic Restarting. A motor running protective device which can restart a motor automatically after overcurrent tripping shall not be installed unless approved for use with the motor it protects. A motor which can restart automatically after shut down shall not be installed so that its automatic restarting can result in injury to persons.

Motor Branch Circuit Overcurrent Protection

4341 General. The following provisions specify overcurrent devices intended to protect the motor, branch circuit conductors, the motor control apparatus, and the motors against overcurrent due to short circuits or grounds. . . .

4342 Ratings or Settings for Individual Motors. The motor branch circuit overcurrent device shall be capable of carrying the starting current of the motor . . . but shall in no case exceed 400% of the motor full load current.

4343 Several Motors on One Branch Circuit. Two or more motors may be connected to the same branch circuit under the following conditions:

a) Two or more motors, each not exceeding one horsepower in rating and each having a full load rated current not exceeding six amperes, may be used on a branch circuit protected at not more than twenty amperes at 125 volts or less, or fifteen amperes at 600 volts or less. Individual running overcurrent protection is unnecessary for such motors unless required by the provisions of section 4322.

b) Two or more motors of any ratings, each having individual running overcurrent protection, may be connected to one branch circuit provided all of the following conditions are complied with:

1. Each motor running overcurrent device must be approved for group installation.
2. Each motor controller must be approved for group installation.
3. The branch circuit must be protected by fuses having a rating equal to that specified in section 4342 for the largest motor connected to the branch circuit plus an amount equal to the sum of the full load currents of all other motors connected to the circuit.
4. The branch circuit fuses must not be larger than allowed by section 4330 for thermal cutout or relay protecting the smallest motor of the group.
5. The conductors of any tap supplying a single motor need not have individual branch circuit protection provided they comply with either of the following: (1) no conductor to the motor shall have a current carrying capacity less than that of the branch circuit conductors, or (2) no conductor to the motor shall have a current carrying capacity less than one-third that of the branch circuit conductors, with a minimum in accordance with section 4312, the conductors to the motor running protective device being not more than twenty-five feet long and being protected from mechanical injury.

4344 Combined Overcurrent Protection. Motor branch circuit overcurrent protection and motor running overcurrent protection may be combined in a single overcurrent device if the rating or setting of the device provides the overcurrent protection specified in section 4322.

Remote Control Circuits

4371 **General.** The following deviations from the general requirements of this code are intended to provide for the peculiar conditions governing remote control circuits.

4372 **Overcurrent Protection.** Conductors of control circuits of remote controlled equipment shall be protected against overcurrent . . . except that such conductors shall be considered as being properly protected by the branch circuit overcurrent devices under any one of the following conditions:

a) If the rating or setting of the branch circuit overcurrent device is not more than 500% of the carrying capacity of the control circuit conductors.

b) If the control device and point of control (start and stop buttons, pressure switch, etc.) are both located on the same machine and the control circuit does not extend beyond the machine.

c) If the opening of the control circuit would create a hazard; as for example, the control circuit of fire pump motors and the like.

4373 **Mechanical Protection of Conductor.** Where damage to a remote control circuit would constitute a hazard, all conductors of such remote control circuit shall be installed in a raceway or be otherwise suitably protected from mechanical injury outside the control device itself.

It is recommended that control circuits be so arranged that an accidental ground will not start the motor.

4374 **Switching.** Control circuits shall be so arranged that they will be disconnected from all source of supply when the disconnect means specified in Section 4406 is in the open position except when a separate switch is used for the control circuit. . . .

Motor Controllers

For the purpose of this article, the term controller included any switch or device normally used to start and stop the motor.

4381 **General.** The following provisions are intended to require suitable controllers for all motors.

4382 **Suitability.** Each controller shall be capable of starting and stopping the motors which it controls. . . .

4383 **Rating.** The controller shall have a horsepower rating which shall not be lower than the horsepower rating of the motor except as follows:

a) Stationary Motor of ⅛ Horsepower or Less. For a stationary motor rated at ⅛ horsepower or less that is normally left running and is so constructed that it can not be damaged by overload or failure to start, such as clock motors and the like, the branch circuit overcurrent device may serve as the controller.

b) Stationary Motors of 2 Horsepower or Less. For a stationary motor of 2 horsepower or less and 300 volts or less, the controller may be a general use switch having an ampere rating at least twice the full load current rating of the motor.

c) Portable Motor of ¼ Horsepower or Less. For a portable motor rated at ¼ horsepower or less, the controller may be an attachment plug and receptacle.

d) Circuit Breaker as Controller. A branch circuit breaker rated in amperes only, may be used as a controller. When this circuit breaker is also used for overcurrent protection, it shall conform to the appropriate provisions of this article governing overcurrent protection.

4384 Need Not Open All Conductors. Except when it serves also as a disconnect means, the controller need not open all conductors to the motor.

4385 In Grounded Conductors. One pole of the controller may be placed in a permanently grounded conductor provided the controller is so designed that the pole in the grounded conductor can not be opened without simultaneously opening all conductors of the circuit.

4386 In Sight from Controller Location. A motor and its driven machinery shall be within sight from the controller location unless one of the following conditions is complied with:

a) The controller or its disconnecting means is capable of being locked in open position.

b) A manually operated switch, which will prevent the starting of the motor, is placed within sight from the motor location. This switch may be placed in the remote control circuit of a remote control type of switch. A distance of more than fifty feet is considered equivalent to being out of sight.

4387 Number of Motors Served by Each Controller. Each motor shall be provided with an individual controller, except that for motors of 600 volts or less, a single controller may serve a group of motors under any one of the following conditions:

a) If a number of motors drive several parts of a single machine or piece of apparatus such as metal and wood working machines, cranes, hoists and similar apparatus.

b) If a group of motors is under the protection of one overcurrent device as permitted in paragraph (a) of section 4343.

c) If a group of motors is located in a single room within sight from the controller location. A distance of more than fifty feet is considered equivalent to being out of sight.

4386 **Adjustable Speed Motors.** Adjustable speed motors, if controlled by means of field regulation, shall be so equipped and connected that they cannot be started under weakened field, unless the motor is designed for such starting.

4389 **Speed Limitation.** Machines of the following types shall be provided with speed limiting devices, unless the inherent characteristics of the machine, the system, or the load and the mechanical connection thereto are such as to safely limit the speed, or unless the machine is always under the manual control of a qualified operator.

a) Separately excited direct current motors.

b) Series motors.

c) Motor generators and converters which can be driven at excessive speed from the direct current end as by a reversal of current or decrease in load.

. . . . .

Disconnecting Means

4401 **General.** The following provisions are intended to require disconnecting means for motors and controllers capable of disconnecting them from the circuit.

4402 **Type.** The disconnecting means shall be a motor circuit switch, rated in horsepower, or a circuit breaker, except as permitted in the following paragraphs a, b, c, or d. Every switch in the motor branch circuit within sight from the controller location shall comply with these requirements.

a) **⅛ Horsepower or Less.** For stationary motors of ⅛ horsepower or less, the branch circuit overcurrent device may serve as the disconnect means.

b) **Two Horsepower or Less.** For stationary motors of two horsepower or less and 300 volts or less, the disconnect means may be a general use switch having an ampere rating of at least twice the full load current rating of the motor.

c) **Exceeding Fifty Horsepower.** For stationary motors rated at more than fifty horsepower, the disconnect means may be a motor-circuit switch also rated in amperes, or an isolating switch.

d) **Portable Motors.** For portable motors, an attachment plug and receptacle may serve as the disconnecting means.

4403 **Carrying Capacity.** The disconnect means shall have a carrying capacity of at least 115 per cent of the name plate rating of the motor.

4404 **Grounded Conductors.** One pole of the disconnecting means may be placed in a permanently grounded conductor if the disconnecting means is so designed that the pole in the grounded conductor can not be opened without simultaneously disconnecting all conductors of the circuit.

4405 **To Be Indicating.** The disconnect means shall plainly indicate whether it is in the open or closed position.

4406 **To Disconnect Both Motor and Controller.** The disconnecting means shall disconnect both the motor and the controller from all ungrounded supply conductors. The disconnecting means may be in the same enclosure with the controller.

4407 **Switch or Circuit Breaker as Both Controller and Disconnecting Means.** A switch or circuit breaker complying with the provisions of section 4383 may serve as both controller and disconnect means if it opens all ungrounded conductors to the motor, is protected by an overcurrent device (which may be branch circuit fuses), which opens all ungrounded conductors to the switch or circuit breaker, and is of one of the following types:

a) An air break switch, operable directly by applying the hand to a lever or handle.

b) A circuit breaker operable directly by applying the hand to a lever or handle.

c) An oil switch used on a circuit whose rating does not exceed 600 volts or 100 amperes if under expert supervision and by special permission. . . .

4408 **Service Switch as Disconnect Means.** If an installation consists of a single motor, the service switch may serve as the disconnecting means, provided it conforms to the requirements of this article and is within sight from the controller location.

4409 **In Sight from Controller Location.** The disconnect means shall be located in sight from the controller location or be arranged to be locked in the open position. A distance of more than fifty feet is considered equivalent to being out of sight.

4410 **Motors Served from a Single Disconnecting Means.** Each motor shall be provided with individual disconnecting means except that for motors of 600 volts or less a single disconnecting means may serve a group of motors under any one of the following conditions. The disconnecting means serving a group of motors shall have a rating not less than is required by section 4402 for a single motor whose rating equals the sum of the horsepowers or currents of all the motors in the group.

a) If a number of motors drive several parts of a single machine or piece of apparatus such as metal and woodworking machines, cranes, and hoists.

b) If a group of motors is under the protection of one set of overcurrent devices as permitted by paragraph (a) of section 4343.

c) If a group of motors is in a single room within sight from the location of the disconnecting means.

4411 Readily Accessible. The disconnecting means shall be readily accessible.

Protection of Live Parts—All Voltages

4431 General. The following provisions specify that live parts shall be protected in a manner judged adequate to the hazard involved.

4432 Where Required. Exposed or live parts of motors and controllers operating at 50 volts or more between terminals except for stationary motors having commutators, collèctors and brush rigging located inside of motor end brackets and not conductively connected to supply circuits operating at more than 150 volts to ground, shall be guarded against accidental contact by enclosure or by location as follows:

a) By installing in a room or enclosure which is accessible only to qualified persons.

b) By installing on a suitable balcony, gallery or platform, or so elevated and arranged as to exclude unqualified persons.

c) By elevation eight feet or more above the floor.

d) So that it will be protected by a guard rail when the motor operates at 600 volts or less.

4433 Guards for Attendants. If the live parts of a motor or controller operating at more than 150 volts to ground are guard against accidental contact only by location as specified in section 4432 and if adjustment or other attendance may be necessary during the operation of the apparatus, suitable insulating mats or platforms shall be provided so that the attendant can not readily touch live parts unless standing on the mats or platforms. When necessary, steps and hand rails should be installed on or about large machines to afford safe access to parts, which must be examined or adjusted during operation.

Grounding

4435 General. The following provisions specify the grounding of motor and controller frames to prevent a potential above ground in event of accidental contact between live parts and frames. Insulation, isolation or guarding are suitable alternatives for motors under certain conditions.

4436 Stationary Motors. The frames of stationary motors shall be grounded if any one of the following conditions exist.

a) If supplied by means of metal clad wiring.

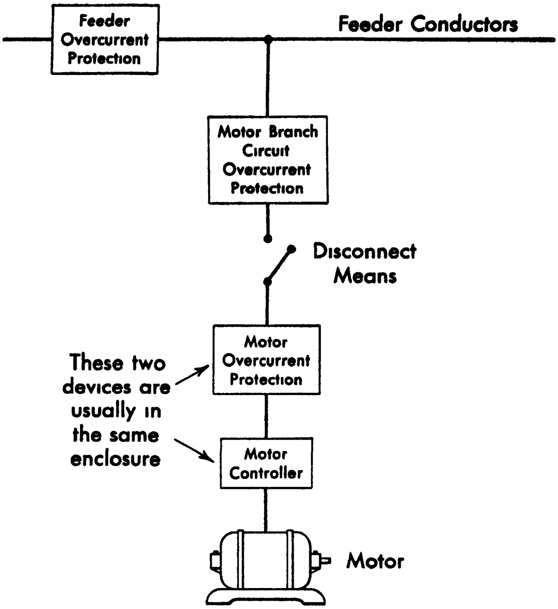

Feeder Overcurrent Protection
Feeder Conductors
Motor Branch Circuit Overcurrent Protection
Disconnect Means
These two devices are usually in the same enclosure
Motor Overcurrent Protection
Motor Controller
Motor

FIG 137 Schematic representation of the requirements of the National Electric Code

b) If located in a wet place and not isolated or guarded

c) If in a hazardous location

d) If the motor operates with any terminal at more than 150 volts to ground Grounding of the motor frame is preferable, but if the frame of the motor is not grounded, it shall be permanently and effectively insulated from the ground

4437 Portable Motors. The frames of portable motors which operate at more than 150 volts to ground shall be guarded or grounded

4438 Controllers. Controller cases, except those attached to underground portable equipment and except the lined covers of snap switches, shall be grounded regardless of voltage

4439 Method of Grounding.

[Author's Note: This section, together with Article 250, give details of grounding. A complete copy of the Code should be consulted for these.]

The National Electric Code gives detailed provisions for many specific applications which have been omitted here. It is the purpose of this chapter to merely outline some of the pertinent points and to give a general idea of the Code and its basic requirements. It should be pointed out that extracts, such as given here, are often misleading and that they are no substitute for the complete Code. Everyone having to do with the installation of electrical equipment should be familiar with all the requirements of the Code and no attempt should be made to change or alter an electrical installation unless supervised by a qualified person who understands all the details of the applicable Code sections.

APPENDIX OF Useful Information

Miscellaneous Definitions

Mil	One thousandth of an inch
Milli	One thousandth of (example: Milliampere)
Micro	One millionth of (example: Microampere)
Mega	One million of (example: Megohm)
Kilo	One thousand of (example: Kilowatt)
Circular Mil	Area of circle .001 inch diameter.
E	Electromotive Force (Volts)
R	Resistance (Ohms)
I	Strength of Current (Amperes)
C	Usually Temperature in degrees Centigrade
F	Usually Temperature in degrees Fahrenheit

Miscellaneous Multipliers

Diameter of circle × 3.1416 = Circumference
Radius of circle × 6.283185 = Circumference
Square of radius of circle × 3.1416 = Area
Square of diameter of circle × 0.7854 = Area
Square of circumference of circle × 0.07958 = Area
Base of triangle × one-half the altitude = Area
Area of base × one-third altitude = Area of cone or pyramid
Altitude of trapezoid × one-half sum of parallel sides = Area
Area of one of its sides × 6 = Total surface of Cube
Square of diameter of sphere × 3.1416 = Surface
Cube of diameter of sphere × 0.5236 = Volume

Prony Brake Test Formula

$$\text{HP} = \frac{2 \times 3.1416 \times \text{Lever in Ft} \times \text{lb} \times \text{rpm}}{33{,}000}$$

Standard Control Device Markings

As recommended by National Elec. Mfgs. Association

Armature acceleration	A	Forward	F
Armature shunt	AS	Full field	FF
Aux. Switch, Norm. open	“a”	Generator field	GF
Aux. Switch, Norm. closed	“b”	High speed	HS
Balanced voltage	BV	Hoist	H
Brake	BR	Jam	J
Capacitor	C	Kick off	KO
Compensator—running	MR	Landing	LD
Compensator—starting	MS	Limit switch	LS
Control	CR	Lowering	L
Door Switch	DS	Low speed	LS
Down	D	Low torque	LT
Dynamic Braking	DB	Low voltage	LV
Field Acceleration	FA	Main or Line	M
Field Deceleration	FD	Master switch	MS
Field Discharge	FD	Maximum torque	MT
Field Dynamic Braking	DF	Middle landing	MLD
Field Failure	FL	Motor field	MF
Field Forcing (decreasing)	DF	Overload	OL
Field Forcing (increasing)	CF	Pilot motor	PM
Field Protective	FP	Plug	P
Field Reversing	FR	Reverse	R
Field Weakening	FW	Series relay	SR
Final Limit—forward	FLF	Slow down	SD
Final Limit—reverse	FLR	Thermostat	TS
Final Limit—hoist	FLH	Time	T
Final Limit—lower	FLL	Up	U
Final Limit—up	FLU	Undervoltage	UV
Final Limit—down	FLD	Voltage relay	VR

Standard Terminal Markings

For D.C. Motors and Control

Line	L1,	L2		
Armature	A1,	A2		
Shunt field	F1,	F2		
Commutating field	H1,	H2,	H3	etc.
Series field	S1,	S2,	S3	etc.
Armature resistance	R1,	R2,	R3	etc.
Field resistance	V1,	V2,	V3	etc.
Braking	B1,	B2		

Centrifugal Force

F = Centrifugal force in pounds
W = Weight of revolving body in pounds
r = Distance from axis of motion to center of gravity of body in feet
N = Number of revolutions per minute
v = Velocity in feet per second

$$F = \frac{Wv^2}{gr} = .00034\ WrN^2$$

Stored Energy in Flywheel

Ft-lb stored energy in flywheel = $E = \frac{1}{2}(Wv^2/g)$
In which:
E = Ft-lb stored energy
W = Weight of flywheel in lb
v = Velocity of radius of gyration in ft per sec.

NOTE: in both of the above, g = acceleration due to gravity = 32.2 ft per sec.

Torque—HP Formula

$$\text{Torque} = \frac{\text{HP} \times 5250}{\text{rpm}}$$

Weight and Resistance of Pure Copper Wire

Wire Gauge Size AWG	Diameter inches	Lbs per 1000 Ft Bare	Feet per pound Bare	Feet per Ohm at 77 F	Ohms per 1000 Ft at 77 F	Carrying cap. in Amps for rubber insulation
0000	.4600	640.5	1.55	20010	.0500	160
000	.4096	507.9	1.97	15870	.0630	138
00	.3648	402.8	2.48	12580	.0795	120
0	.3248	319.5	3.13	9980	.1002	105
1	.2893	253.3	3.95	7914	.1264	91
2	.2576	200.9	4.98	6276	.1593	80
3	.2294	159.3	6.28	4977	.2009	69
4	.2043	126.4	7.91	3947	.2533	60
5	.1819	100.2	9.98	3120	.3195	52
6	.1620	79.5	12.58	2482	.4028	45
8	.1284	50.0	20.01	1561	.6405	35
10	.1018	31.4	32.82	981.8	1.018	25
12	.0808	19.8	50.59	617.5	1.619	20
14	.0640	12.4	80.44	388.3	2.575	15
16	.0508	7.82	127.90	244.2	4.094	
18	.0403	4.92	203.40	153.6	6.510	
20	.0319	3.09	323.4	96.6	10.35	
22	.0254	1.95	514.2	60.75	16.46	
24	.0201	1.22	817.7	38.21	26.17	
26	.0159	.77	1300	24.03	41.62	
28	.0126	.48	2067	15.11	66.17	
30	.0100	.30	3287	9.50	105.2	
32	.0080	.19	5227	5.98	167.3	
34	.0063	.12	8310	3.76	266.0	
36	.0050	.076	13210	2.36	423.0	
38	.0040	.047	21010	1.49	672.6	
40	.0031	.030	33410	.935	1069	
42	.0025	.019	53800	.588	1701	
44	.0020	.012	82500	.370	2703	
46	.0016	.008	128800	.233	4299	
48	.0012	.004	229600	.146	6836	
50	.0010	.003	330000	.092	10870	

Suggested Wiring for D.C. Motors

Carrying capacity of copper wire with rubber insulation

Size B & S	Dia. Inches	Pounds per 1,000 Ft Bare Copper	Carrying capacity Amperes
14	.064	12.4	15
12	.081	19.7	20
10	.102	31.4	24
8	.128	49.9	33
6	.162	79.4	46
4	.204	126	65
3	.229	159	76
2	.258	201	90
1	.289	253	107
0	.325	319	127
00	.365	402	150
000	.410	507	177
0000	.460	640	210

Direct Current Power Formulas

Given	To Find	Formula
Volts & Amps	H.P.	$\frac{I \times E \times \% \text{ Eff.}}{746}$
Horsepower	Amperes	$\frac{\text{H.P.} \times 746}{E \times \% \text{ Eff.}}$
Volts & Amps	Kilowatts	$\frac{I \times E}{1000}$
Kilowatts	Amperes	$\frac{\text{K.W.} \times 1000}{E}$

Average Ampere Ratings of D.C. Motors

H.P.	115 Volts	230 Volts	550 Volts
⅛	1.4	.7	.3
⅙	1.8	.9	.4
¼	2.3	1.2	.5
½	4.5	2.3	1.0
¾	6.5	3.3	1.4
1	8.4	4.2	1.7
1½	12.5	6.3	2.6
2	16.1	8.3	3.4
3	24.0	12.3	5.0
4	32	16.1	6.6
5	40	19.8	8.2
7½	50	28.7	12.0
10	75	38	16.0
12½	94	47	19.5
15	112	56	23
20	148	74	30
25	185	92	38
30	220	110	45
35	257	128	53
40	294	146	61
45	330	163	68
50	364	180	75
60	436	215	90
75	540	268	111
90	648	322	132
100	720	357	146
125	890	443	184
150	1060	528	220
175	1240	617	257
200	1415	705	295

NOTE: The above table is for average full load amperes. The exact ampere full load rating will vary somewhat with the type and make of the motor.

See also table taken from the 1947 edition of National Electric Code.

Allowable Current Carrying Capacity of Conductors in Amperes

(Not more than 3 conductors in raceway or cable)

WIRE SIZE	RUBBER Type R Type RW Type RU Thermoplastic Type T Type TW	RUBBER Type RH	ASBESTOS Varn-Camb. Type AVA Type AVL	IMPREG. ASBESTOS Type AI Type AIA	ASBESTOS Type A Type AA
14	15	15	30	30	30
12	20	20	35	40	40
10	30	30	45	50	55
8	40	45	60	65	70
6	55	75	80	85	95
4	70	85	105	115	120
3	80	100	120	130	145
2	95	115	135	145	165
1	110	130	160	170	190
0	125	150	190	200	225
00	145	175	215	230	250
000	165	200	245	265	285
0000	195	230	275	310	340
250 MCM	215	255	315	335	
300 MCM	240	285	345	380	
350 MCM	260	210	390	420	
400 MCM	280	335	420	450	
500 MCM	320	380	470	500	
(Single conductor in free air)					
14	20	20	40	40	45
12	25	25	50	50	55
10	40	40	65	70	75
8	55	65	85	90	100
6	80	95	120	125	135
4	105	125	160	170	180
3	120	145	180	195	210
2	140	170	210	225	240
1	165	195	245	265	280
0	195	230	285	305	325
00	225	265	330	355	370
000	260	310	385	410	430
0000	300	360	445	475	510
250 MCM	340	405	495	530	
300 MCM	375	445	555	590	
350 MCM	420	505	610	655	
400 MCM	455	545	665	710	
500 MCM	515	620	765	815	

Motor Over-Current Protection

Motor Full Load Rating in Amperes	Maximum rating for NON adjust. devices	Maximum rating for Adjustable devices	Max. Rating of branch circuit protection.
	Amp	Amp	Amp
1	2	1.25	15
2	3	2.50	15
3	4	3.75	15
4	6	5.0	15
5	8	6.25	15
6	8	7.50	15
7	10	8.75	15
8	10	10.0	15
9	12	11.25	15
10	15	12.50	15
11	15	13.75	20
12	15	15.0	20
13	20	16.25	20
14	20	17.50	25
15	20	18.75	25
16	20	20.00	25
17	25	21.25	30
18	25	22.50	30
19	25	23.85	30
20	25	25.0	30
22	30	27.50	35
24	30	30.0	40
26	35	32.50	40
28	35	35.0	45
30	40	37.50	45
32	40	40.0	50
34	45	42.50	60
36	45	45.00	60
38	50	47.50	60
40	50	50.00	60
42	50	52.50	70
44	60	55.0	70
46	60	57.50	70
48	60	60.0	80
50	60	62.50	80
60	80	75.0	90
70	90	87.50	110
80	100	100.00	125
90	110	112.50	150
100	125	125.00	150
110	150	137.50	175
120	150	150.00	200
130	175	162.50	200
140	175	175.0	225
150	200	187.5	225
175	225	219	300
200	250	250	300

Table of Voltage Drop

WIRE SIZE		PERCENTAGE OF VOLTAGE DROP				
110 Volts	220 Volts	1%	2%	3%	5%	10%
	0000	21,550	43,100	64,650	107,750	215,500
	000	17,080	34,160	51,240	85,400	170,800
	00	13,550	27,100	40,650	67,750	135,500
0000	0	10,750	21,500	32,250	53,750	107,500
000	1	8,520	17,080	25,560	42,600	85,200
00	2	6,750	13,520	20,280	33,800	67,600
0	3	5,360	10,720	16,080	26,800	53,600
1	4	4,250	8,500	12,750	21,250	42,500
2	5	3,370	6,740	10,110	16,850	33,700
3	6	2,670	5,340	8,010	13,350	26,700
4	7	2,120	4,240	6,360	10,600	21,200
5	8	1,680	3,360	5,040	8,400	16,800
6	9	1,330	2,660	3,990	6,650	13,300
7	10	1,055	2,110	3,165	5,275	10,550
8	11	838	1,675	2,514	4,190	8,380
9	12	665	1,330	1,995	3,320	6,650
10	13	527	1,054	1,580	2,635	5,720
11	14	418	836	1,254	2,090	4,180
12		332	665	997	1,660	3,325
13		209	418	627	1,045	2,900

Explanation of Table

The voltage drop depends on both the amount of current carried in amperes and the length of the line (length of ONE wire). The figures in the above table under the percentage headings represent distance × amperes. Distance is taken as the length of one wire.

Example: Using #10 wire at 220 volts, one ampere can be transmitted 5,275 feet with a voltage drop of 5%.

Problem: What size wire should be used to transmit 10 amps at 220 volts at distance of 158 feet allowing a voltage drop of 3%? From the table under the heading of 3% find 1580 (distance times amperes) and the wire size at 220 volts will be #13.

Equivalents of Wires

Showing approximately equal capacities in the use of conductors of different sizes as a substitute for large size single conductors.

Total Capacity Circ. Mils.	Use 2 of	Use 3 of	Use 4 of	Use 5 of	Use 6 of	Use combination of the two shown	
1,000,000	—	—	—	0000	000		
800,000			0000	000	00		
600,000		0000	000	00	0		
500,000		000	00	0	1		
400,000	0000	00	0	1	2		
350,000	000	—	1	2	—	0000 & 00	
300,000	—	0	2	—	3	000 & 00	0000 & 1
250,000	00	1	—	3	4	000 & 1	0000 & 4
0000	0	2	3	4	5	00 & 1	000 & 2
000	1	3	4	5	6	0 & 2	00 & 5
00	2	4	5	6	—	1 & 3	0 & 6
0	3	5	6	—	8	2 & 4	
1	4	6	—	8	—	3 & 5	
2	5	—	8	—	—	4 & 6	
3	6	8	—	10	—	—	
4	—	—	10	—	—	6 & 8	
5	8	10	—	12	—	—	
6	—	—	12	—	14	8 & 10	
8	—	—	14	—	16	10 & 12	
10	—	—	16	—	18	12 & 14	

Conductor Insulation

Trade Name	Type Letter	Insulation Material
Rubber covered fixture wire (Solid or Stranded)	RF	Code rubber
Rubber covered fixture wire, flexible stranding	FF	Code rubber
Thermoplastic covered fixture wire	TF	Thermoplastic composition
Thermoplastic covered fixture wire flexible	TFF	Thermoplastic composition
Cotton covered, heat resistant fixture wire	CF	Impregnated cotton
Asbestos covered heat resistant fixture	AF	Impregnated asbestos
Code wire	R	Code rubber
Heat resistant	RH	Heat resistant rubber
Moisture resistant	RW	Moisture resistant rubber
Latex	RU	Unmilled rubber
Thermoplastic	T	Thermoplastic composition
Moisture resistant thermoplastic	TW	Moisture resistant thermoplastic composition
Thermoplastic and asbestos	TA	Thermoplastic and asbestos
Varnished cambric	V	Varnished cambric
Asbestos and varnished cambric	AVA AVL	Asbestos and varnished cambric L signifies lead sheath
Slow burning	SB	Impregnated fire retardant cotton thread
Weatherproof	WP	Impregnated cotton braid (At least 3 layers)
Paper	—	Paper insulation in lead sheath

Electric Conductivity

Relative Electric Conductivity as compared with Silver

Silver	100	Cadmium	24.38	Iron	14.57	Palladium	12.00
Copper	97.61	Calcium	21.77	Platinum	14.43	Steel	12.00
Gold	76.61	Rubidium	20.46	Tin	14.37	Thallium	9.13
Aluminum	63.00	Cesium	20.00	Tungsten	14.00	Lead	8.42
Tantalum	54.63	Lithium	18.68	Osmium	13.98	Columbium	5.13
Magnesium	39.44	Molybdenum	17.60	Titanium	13.73	Vanadium	4.95
Sodium	31.98	Cobalt	16.93	Iridium	13.52	Arsenic	4.90
Beryllium	31.13	Uranium	16.47	Ruthenium	13.22	Antimony	3.59
Barium	30.61	Chromium	16.00	Nickel	12.89	Mercury	1.75
Zinc	29.57	Manganese	15.75	Rhodium	12.60	Bismuth	1.40
Indium	26.98					Tellurium	0.001

Table of Resistance Materials

Name of Material	Composition	Resistance Ohms per Cir. Mil. Foot	Maximum Working Temp. F	Approx. Melting Point F.
Copper	Annealed	10.4	500 F.	1980 F.
Platinum	Pure	57.4	2700	3190
German Silver	18% Copper-Nickel-Zinc.	200	500	1880
German Silver	30% Copper-Nickel-Zinc	290	500	2120
Ia Ia Soft	Copper-Nickel	283	700	2250
Advance	Copper-Nickel	294	700	2300
Constantin	Copper-Nickel	300	700	2200
Ideal	Copper-Nickel	300	700	2200
Krupp	Nickel-Steel	511	1100	2400
Climax	Nickel-Steel	525	1000	2300
Nichrome	Nickel-Chromium	600	2200	2800
Nichrome II	Nickel-Chromium	655	2200	2850
Ohmax	Iron-Chrom-Alum.	1000	500	1500

Temperature Conversion Table

Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.
0	32	25	77.0	50	122.0	76	168.8
1	33.8	26	78.8	51	123.8	77	170.6
2	35.6	27	80.6	52	125.6	78	172.4
3	37.4	28	82.4	53	127.4	79	174.2
4	39.2	29	84.2	54	129.2	80	176.0
5	41.0	30	86.0	55	131.0	81	177.8
6	42.8	31	87.8	56	132.8	82	179.6
7	44.6	32	89.6	57	134.6	83	181.4
8	46.4	33	91.4	58	136.4	84	183.2
9	48.2	34	93.2	59	138.2	85	185.0
10	50.0	35	95.0	60	140.0	86	186.8
11	51.8	36	96.8	61	141.8	87	188.6
12	53.6	37	98.6	62	143.6	88	190.4
13	55.4	38	100.4	63	145.4	89	192.2
14	57.2	39	102.2	64	147.2	90	194.0
15	59.0	40	104.0	65	149.0	91	195.8
16	60.8	41	105.8	66	150.8	92	197.6
17	62.6	42	107.6	67	152.6	93	199.4
18	64.4	43	109.4	68	154.4	94	201.2
19	66.2	44	111.2	69	156.2	95	203.0
20	68.0	45	113.0	70	158.0	96	204.8
21	69.8	46	114.8	71	159.8	97	208.6
22	71.6	47	116.6	72	161.6	98	208.4
23	73.4	48	118.4	73	163.4	99	210.2
24	75.2	49	120.2	74	165.2	100	212.0
				75	167.0		

Glossary

a-c, abbreviation for alternating current.

Across-the-line starter, a type of starter arranged to place the full-line voltage on the machine without any intermediate resistor steps.

Adjustable resistor, a resistor so constructed that its resistance can be readily changed.

Adjustable speed motor, one which can be varied in speed over a considerable range, but when once adjusted, remains practically unaffected by the load.

Ambient, surrounding. Ambient temperature; surrounding temperature; loosely, room temperature.

Ampere, the practical unit of rate of flow of an electric current.

Anode, the electrode in a vacuum tube which receives the emitted electrons, often called the *plate*.

Arc shield, a barrier of insulating material for the isolation of electric arcs.

Armature, in a motor or generator, a core around which a winding is mounted, so built as to rotate in a magnetic field.

Armature reaction, the effect resulting from the electromagnetic action set up by the rotating armature.

Auxiliary contacts, small contacts which open and close the control circuit.

Back pitch, in an armature winding, the number of coil sides between the point at which a given conductor leaves the armature core and that at which it re-enters at the back of the armature.

Bi-polar, a machine having two magnetic poles.

Blow-out coil, a magnetic coil so placed that it will blow out the arc formed by the opening of a contactor.

Breakaway torque, the total torque developed in a motor armature to start rotation.

Brush, a device, usually in the form of a carbon block, which makes electrical contact with the commutator of an electrical machine, and through which the current flows between the armature windings and the external circuit.

Brush shunt, a short length of flexible wire which carries the current between the brush and the brush rigging.

Cam controller, a form of drum controller in which the contact fingers are actuated by cams mounted on a rotating shaft.

Capacitor, a device capable of storing electric energy in the form of electric charges.

Cathode, the electrode in an electronic tube which emits electrons.

Circuit, the complete continuous path followed by an electric current.

Circuit breaker, a device designed to open an electric circuit by the operation of an electromagnetic or thermal device for the purpose of protecting that circuit and connected electrical equipment against abnormal conditions, such as short circuits or overloads, which might cause damage.

Clapper contactor, a form of magnetic contactor hinged at one end for the opening or closing of an electric circuit.

Clearance, in a motor or generator, the open space occurring between the pole faces of the field magnet and the surface of the armature.

Closed cycle control, a control system which is self-regulatory.

Coil pitch, the number of coil sides or the number of slots between the point at which a given conductor leaves the armature core and that at which it re-enters.

Commutator, an assembly of conducting members, individually insulated, in a supporting structure with an exposed surface for contact with current-collecting brushes and ready for mounting on an armature shaft.

Commutating pole, *see* Interpole.

Compensating winding, a winding designed to neutralize the armature cross field, wound in series with the armature through slots across the face of the pole pieces.

Compound wound, an electric generator or motor with field windings arranged partly in series and partly in parallel with the armature winding.

Contact drop, the drop in voltage due to the resistance between the face of the brush and the surface of the commutator.

Contact wear allowance, the total thickness of material which may be worn away before the contact of two associated surfaces becomes inadequate to carry its rating.

Copper loss, the loss of electric energy resulting from the resistance offered to the flow of the current through a copper conductor.

Counter electromotive force, an opposing electromotive force which resists the current flow in a circuit.

Cumulative compound, a field winding of a compound motor or generator so connected that the series winding and the shunt winding aid each other in the production of magnetic flux.

d-c, abbreviation for direct current.

Dash pot, a device usually consisting of a cylinder and piston arrangement with an orifice through which air or oil is forced, used to retard any sudden action.

Definite time delay, a term applied to a device whose time of operation is substantially constant, regardless of the magnitude of the quantity that causes the action.

Dielectric strength, the maximum voltage that an insulating substance will resist without permitting a disruptive discharge through it.

Differential compound, a field winding of a compound motor or generator so connected that the series winding and the shunt winding oppose each other in the production of magnetic flux.

Drop-out, a term popularly applied to the opening of a magnetic contactor or to the reduced voltage at which it opens.

Drum controller, a type of manual controller in which the electric contacts are made between stationary fingers and segments on a rotating cylinder.

Duplex winding, an armature winding with four paths through the armature from each brush.

Dynamic balance, a condition wherein all rotational forces are in a state of balance or equilibrium.

Dynamic braking, a system of electric braking in which the motor is used as a generator and the energy produced absorbed by suitable resistors.

Eddy currents, induced electric currents occurring when a solid metallic mass is rotated in a magnetic field.

Effectual electromotive force, the arithmetic difference between the impressed electromotive force and the counter electromotive force.

Electrical degree, the 360th part of the angle subtended, at the axis of the machine, by two consecutive field poles of like polarity.

Electro-magnet, a magnet produced by a current of electricity passing through a coil of wire wound around an iron core.

Electromotive force, the electric pressure which tends to impel an electric current in a circuit. The practical unit of electromotive force is the volt.

Equalizers, in a motor or generator, connections of low resistance to prevent armature circulating currents from passing through the brushes.

Exciter, an auxiliary generator which supplied energy for the field excitation of another machine.

Exciter regulator, a form of generator with special windings so connected that its output is responsive to small changes in the control circuit, used to supply the field excitation of another machine.

Face plate starter, a form of manual starter with a movable arm which sweeps over a row of stationary contacts mounted on a flat surface for the purpose of removing steps of resistance from the circuit.

Field, electrical stress produced in space due to magnetic lines of force or by electrical charges.

Field coil, a suitable insulated winding to be mounted on a field pole to magnetize it.

Field magnet, is a magnet used to produce a magnetic field in an electrical machine.

Flashover, in a motor or generator, is a disruptive discharge around or over the surface of the commutator.

Flux, magnetic or electrostatic force produced by the flow of electricity or magnetism.

Fractional horsepower, a term popularly applied to all motors whose normal rating is less than one horsepower.

Frame, is the supporting structure for the stator parts and usually forms a part of the magnetic circuit. It includes the poles only when they form an integral part of it.

Front pitch, is the number of coil sides between the point at which a given conductor leaves the armature core and that at which it re-enters, on the front or commutator side of the armature.

Fuse, an overcurrent protective device with a circuit opening fusible member directly heated and destroyed by the passage of overcurrent through it.

Generator, a machine which transforms mechanical energy into electrical energy.

Grid, in an electronic tube, is an electrode having one or more openings for the passage of electrons and usually used to control their flow.

Grid resistor, is a resistance usually in the form of a zig-zag grating of metal strips or bars introduced in an electric circuit to increase the resistance of that circuit.

Ground, an electrical connection, accidental or intentional, made to the earth. In the case of an electrical machine, a connection to the machine frame.

Growler, a device consisting of a yoke magnetized by a primary winding for the purpose of inducing a voltage in an armature coil to detect winding faults.

Holding Magnet, an electric contactor used to hold the main circuit closed after the control circuit has been opened.

Horsepower, the unit of mechanical power. The power required to raise 33,000 pounds one foot in one minute. Equal to 746 watts.

Hunt, to swing back and forth alternately overshooting and undershooting a desired fixed point in effort to seek equilibrium.

Hysteresis, an expenditure of energy in the form of heat when a magnetic material undergoes rapid changes or reversals of magnetism.

IR drop, the voltage drop due to the flow of current through a resistance.

I^2R loss, the energy (heat) loss due to the flow of current through a resistance.

Ignitron, a type of electronic tube with a pool of mercury for the cathode and an electrode known as the ignitor to establish the electron flow in addition to the usual anode.

Impressed electromotive force, the electromotive force supplied to a circuit from an external source to cause a flow of current.

Inching, *see* Jogging.

Induction, the production of an electrical or magnetic effect by one body upon another without actual contact.

Inductor, in a motor or generator, the straight portion of an armature coil which cuts through the magnetic field.

Industrial analyzer, a set of test meters conveniently mounted in a portable case, used to measure the electrical characteristics of a machine under operating conditions.

Inner race, the rotating inner ring of a ball bearing.

Inrush current, the maximum value of the current at the instant a motor at rest is connected to the supply line.

Insulation resistance, the opposition to the flow of current offered by the nonconductive covering of an electric conductor. Perfect insulation would have an infinite insulation resistance.

Integral horsepower, a term popularly applied to all motors whose normal rating is one or more horsepower.

Interpole, an auxiliary magnetic pole placed between the main field poles of an electric machine, the purpose of which is to permit proper commutation.

Inverse time delay, is a term applied to a device whose time of operation decreases as the operating force increases.

Iron loss, a term popularly applied to the loss of energy in an electric machine due to the hysteresis and eddy current in the iron mass.

Jogging, is the quickly repeated closure of the circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine.

Junction box, a box or enclosure in which electric circuits are connected.

Kilo, a prefix meaning one thousand.

Kilowatt, one thousand watts.

Lamination, building up a mass of metal of flat thin plates or sheets.

Lap winding, a form of armature winding in which the coil wires lap backwards towards the point at which the winding began.

Limit switch, a switch automatically operated by the travel of a carriage to open the circuit and thus limit its travel.

Low voltage protection, is the effect of a device operative on the reduction or failure of voltage to cause and maintain the interruption of power to the main circuit.

Low voltage release, is the effect of a device operative on the reduction or failure of voltage to cause interruption of power to the main circuit but not to prevent the re-establishment of the main circuit on the return of voltage.

Magnetic contactor, is a device for repeatedly establishing and interrupting an electric power circuit by electromagnetic means.

Magnetic controller, is an electric controller having all its basic functions performed by electro-magnets.

Magnetic field, the region surrounding a magnet through which magnetic forces act.

Magnetic pole, one of the two ends of a magnet where most of the magnetic activity appears to be concentrated.

Manual controller, is an electric controller having all its basic functions performed by hand.

Master switch, is a switch which dominates the operation of contactors, relays or other magnetically operated devices.

Megger, a registered trade name (James G. Biddle Co.) applied to instruments used to measure high resistance.

Megohm, one million ohms.

Moment of inertia, in a rotating body, is the sum of the products of the mass of each particle of matter of the body into the square of its distance from the axis of rotation.

Motor, a machine which converts electrical energy into mechanical energy.

Multiplex winding, is an armature winding with two or more separate sets of coils forming four or more separate paths through the armature from each brush.

Multiple switch controller, a mechanism consisting of a series of toggle operated switches, each of which removed a step of resistance when closed for the purpose of reduced voltage starting.

Multipolar machine, is a machine having more than two field poles but always an even number of poles.

Neutral point, in a motor or generator, the point midway between field poles where the direction of the current in the armature inductors reverses.

No voltage protection, *see* Low voltage protection.

No voltage release, *see* Low voltage release.

Ohm, the practical unit of electrical resistance.

Outer race, the stationary outer ring of a ball bearing.

Over motoring, an excessively large motor for the required mechanical load.

Parallel, that arrangement of an electrical system in which all the positive terminals are joined to one conductor and all the negative terminals to another conductor.

Permeability, magnetic, is the measure of the ease with which magnetism passes through any substance.

Pick-up, a term popularly applied to the closing of a magnetic contactor or to the increase in voltage which causes it to close.

Pig-tail, a term popularly applied to a short length of extra flexible connecting wire, usually on a carbon brush.

Plugging, throwing a motor from full speed in one direction to full speed in the opposite direction.

Pole piece, is a piece of ferromagnetic material forming one end of a magnet and so shaped as to control the distribution of the magnetic flux in the adjacent medium.

Power loop, the main power circuit between the generator and the driving motor in the Ward Leonard control system.

Progressive winding, an armature winding having a greater back pitch than front pitch.

Prony brake, a mechanical device to enable computing the power delivered by a revolving shaft consisting of a a clamping device applied to a pulley with a lever arm and suitable means to measure the lever arm weight.

Protective panel, is a panel on which protective devices, usually relays, are mounted which function to prevent or limit damage to apparatus.

Regenerative braking, a system of electric braking in which the motor is used as a generator and the energy produced is returned to the supply system.

Relay, a device, by means of which contacts in one circuit are operated by a change in conditions in the same circuit or in one or more associated circuits.

Relay heater, a thermal device which functions on sustained overload to open the circuit.

Reluctance, magnetic, the resistance offered to the magnetizing flux by the substance being magnetized.

Residual magnetism, the magnetism permanently retained in a piece of iron after the magnetizing agent has been removed.

Resistance, the inherent opposition of an electric circuit to the flow of electric current. It depends primarily on the properties of the substance used as a conductor.

Retrogressive winding, an armature winding having a greater front pitch than back pitch.

Rheostat, an adjustable resistor so constructed that its resistance can be changed without opening the circuit to which it is connected.

Series circuit, that arrangement of an electrical system in which the separate parts of the circuit are successively connected end to end to form a single path for the current.

Series wound, a type of winding in a motor or generator so connected that the entire current of the external circuit passes through both the field and the armature coils.

Shorted-out, a means of removing a device from an electric circuit by short circuiting its terminals.

Shunt, a branch conductor connected in parallel with the main conductor or a device arranged to permit only a small portion of the current of a circuit to energize a sensitive instrument.

Shunt wound, a type of winding in an electric motor or generator so connected that the armature coils and the field coils are connected in parallel.

Simplex winding, is an armature winding with only two paths through the armature from each brush.

Solenoid, a hollow cylindrical winding which acquires the properties of a magnet when a current flows through it.

Solenoid contactor, a form of magnetic contactor which functions by the action of a solenoid coil on a movable plunger for the repeated opening or closing of an electric circuit.

Speed regulation, is the change in speed with a change in load expressed as a percentage of the speed at full rated load.

Stabilized shunt motor, is a shunt wound motor having a light series winding added to prevent a rise in speed or to obtain a slight reduction in speed with increase of load.

Starter, an electric controller for accelerating a motor from rest to normal speed.

Surge, the sudden rush of electric current in a circuit at the instant the circuit is closed or a sudden load thrown on it.

Switch, any device by means of which an electric circuit may be opened or closed.

Tachometer, a device for indicating the speed of rotation.

Terminal, a point at which a connection is made between an electrical apparatus and the external circuit.

Thermal relay, is a relay controlled by the heating effect of motor current for the purpose of cutting off the current if the motor approaches an unsafe degree of heating.

Thyratron, an electronic tube containing inert gas or mercury vapor under low pressure and three electrode elements.

Torque, tangential force that tends to produce rotation, measured in pounds at one foot radius.

Undercutting, the operation of cutting away the mica insulation between commutator bars to prevent it from projecting above the commutator surface.

Universal motor, a series wound motor which may be operated on either direct current or single phase alternating current at approximately the same speed and output.

Variable resistance, *see* Adjustable resistor.

Varying speed motor, is one the speed of which varies with the load.

Volt, the practical unit of electromotive force.

Ward Leonard Control, a system of

speed control in which the drive motor is powered by a generator with a variable voltage output.

Watt, a unit of electric power. In a direct current circuit it is that amount of power produced by a current of one ampere at a pressure of one volt.

Wave winding, a method of arranging the coils of an armature winding in which the conductor travels around the armature without turning back until all coils are connected.

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